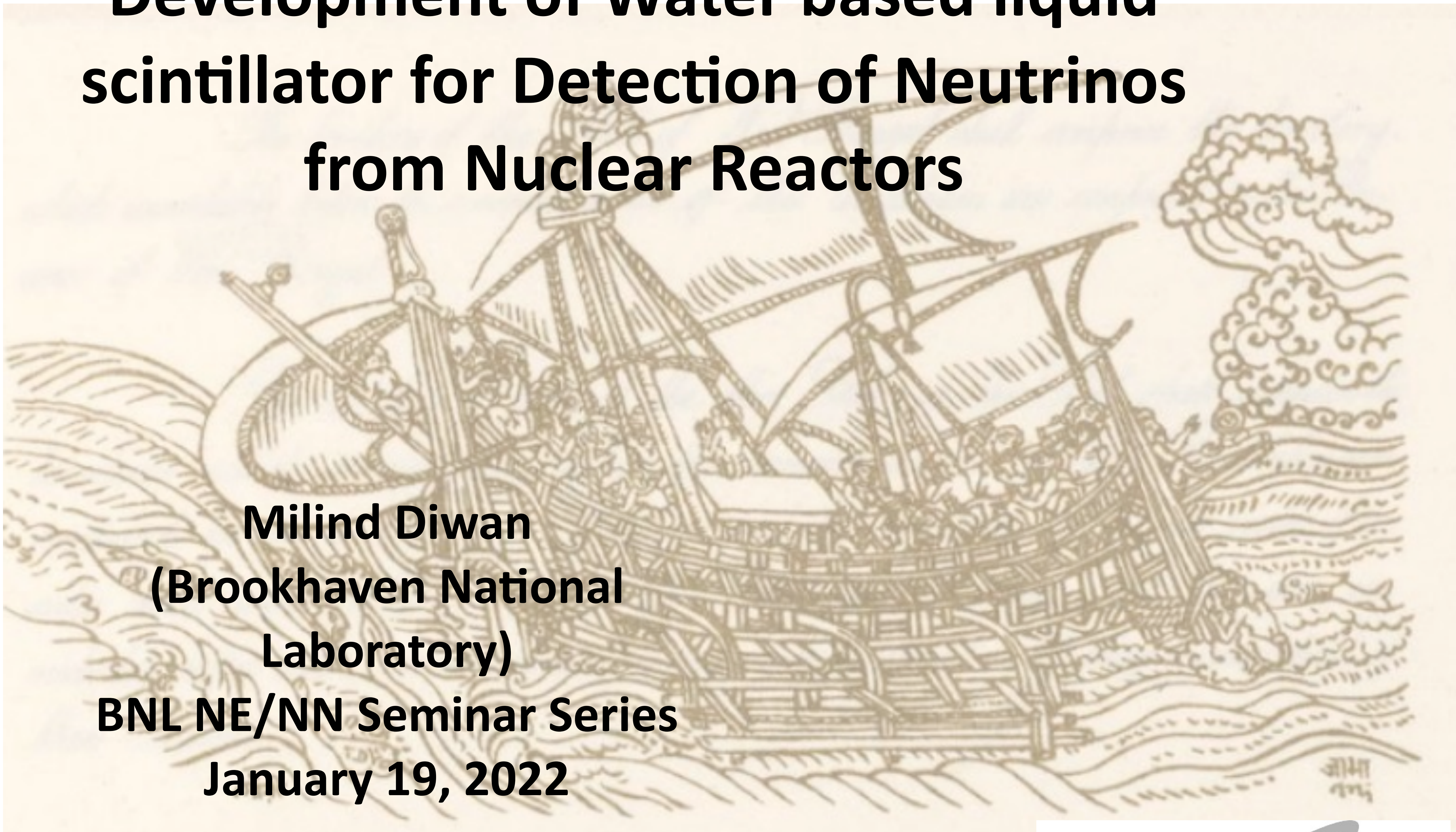


Development of Water based liquid scintillator for Detection of Neutrinos from Nuclear Reactors

Milind Diwan
(Brookhaven National Laboratory)

BNL NE/NN Seminar Series
January 19, 2022

BROOKHAVEN
NATIONAL LABORATORY

Outline

- **Summary of Neutrino Characteristics**
- **Detector Requirements for reactor antineutrinos**
- **Examples of Reactor antiNeutrino Detectors**
- **Reactor antiNeutrinos and Non-proliferation**
- **Development of water based scintillation technology for reactor antineutrinos.**

Some Reading material:

Light: https://kids.frontiersin.org/article/10.3389/frym.2020.00045

Heavy: https://www.annualreviews.org/doi/full/10.1146/annurev-nucl-102014-021939

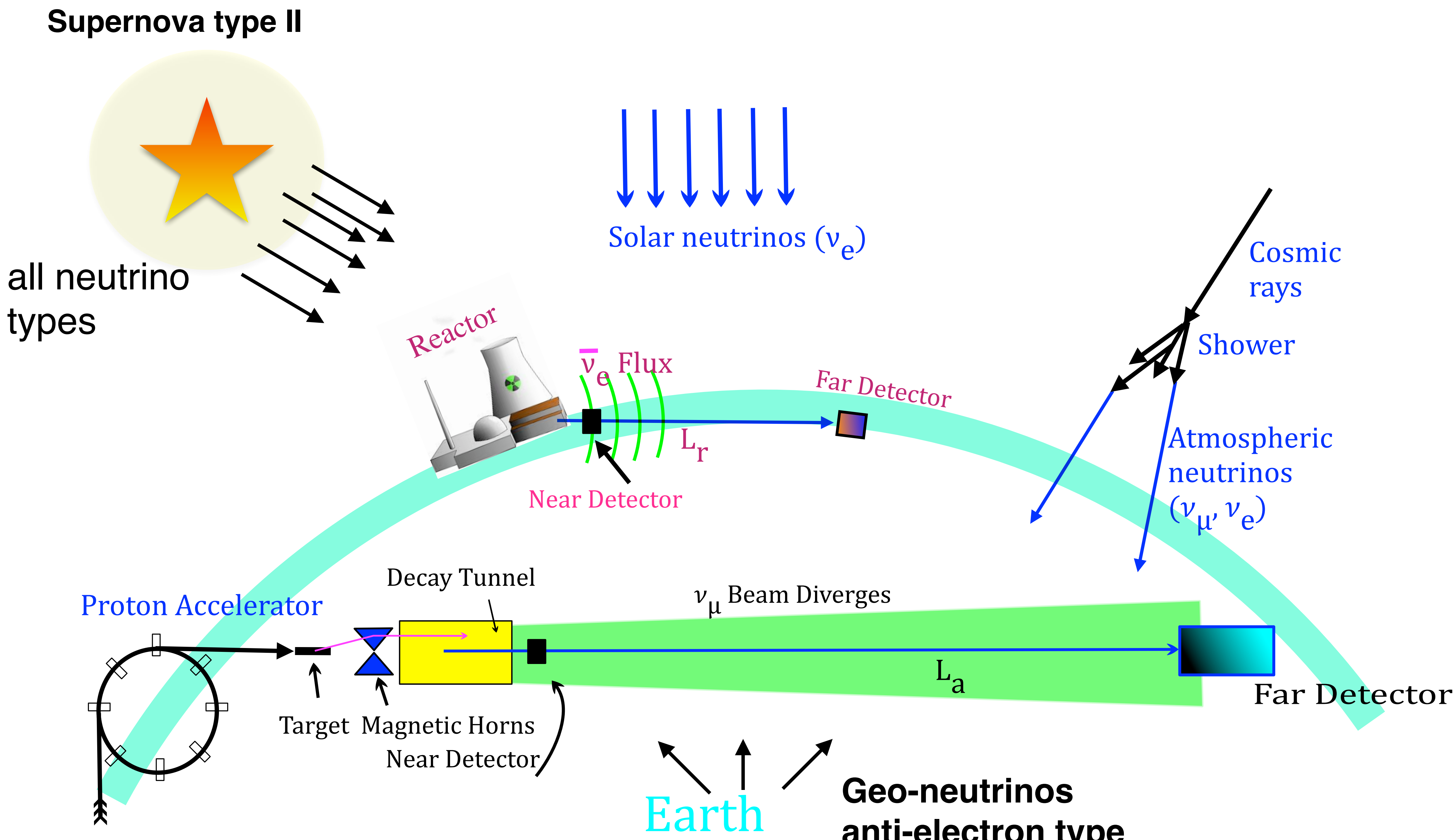
Three types of Neutrinos. We can only detect these. They are grouped together with charged partners.

Particles in this table are called leptons (Greek root: leptos)

Particle	Symbol	Charged Mass	Associated Neutrino	Also Anti-neutrino
Electron	e	1	ν_e	$\bar{\nu}_e$
Muon	μ	200	ν_μ	$\bar{\nu}_\mu$
Tau	τ	3500	ν_τ	$\bar{\nu}_\tau$
	Negative Electrical Charged		Neutral	

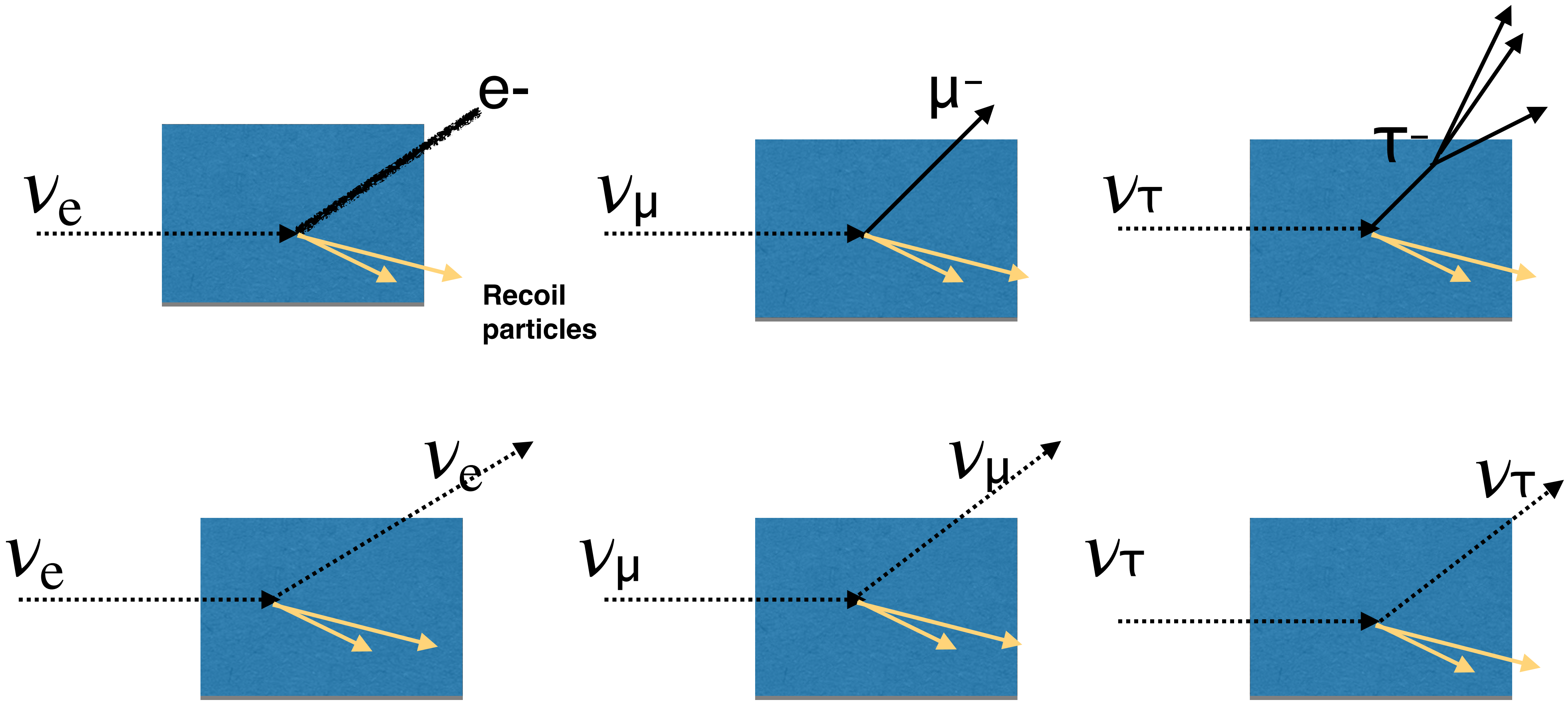
In any given weak interaction the leptons always appear in pairs. (e+ e-) or (e+ ν_e), etc. (opposite charged particles are called anti-particles)

Neutrino Sources



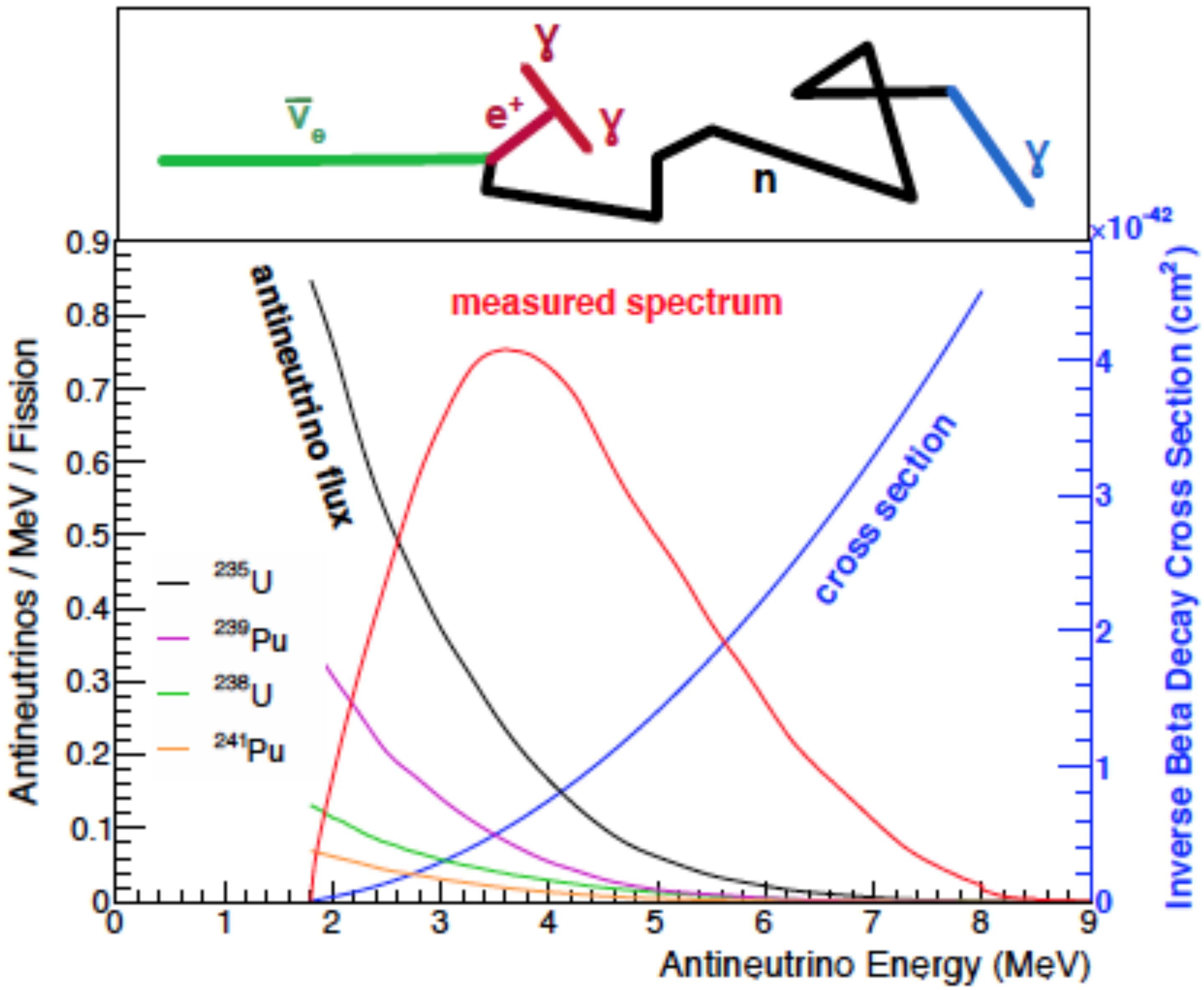
Natural and manmade sources of led us to understand the properties of neutrinos in much greater detail. Annual Rev. 66, 2016.

Neutrino Detection



- **The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.**
- **Neutrino collision on atoms in detectors produces a charged lepton. (Charged Current)**
- **The electron, muon, tau have very different signatures in a detector.**
- **Neutrino can also collide and scatter away leaving observable energy.(Neutral Current)**

Nuclear Reactor Events and spectrum



Typical Power reactors produce 3 GW of thermal energy.

Each fission has ~200 MeV.

Each fission leads to 6 beta decays.

Beta decays produce electron antineutrinos.

These anti-neutrinos have inverse beta decay reactions on protons in a detector.

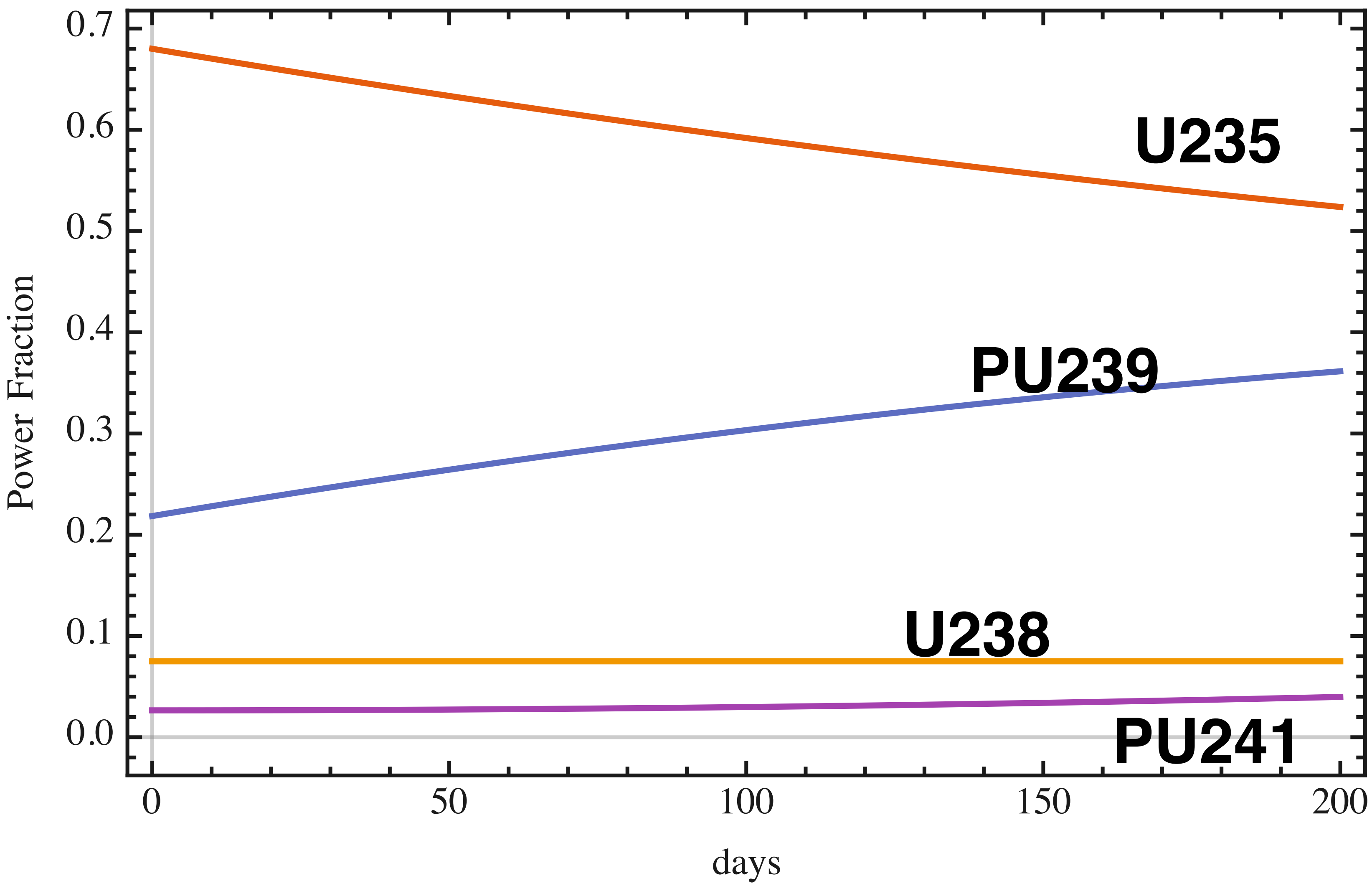
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$Neutrinos/\sec = 6\frac{3\times 10^9\, J/\sec}{1.6\times 10^{-13}\, J/MeV \bullet 200\, MeV} = 6\times 10^{20}/sec$$

for 3 GW Thermal power.

Find how to calculate the spectrum from literature. (P. Vogel et al.)

How to calculate reactor spectra



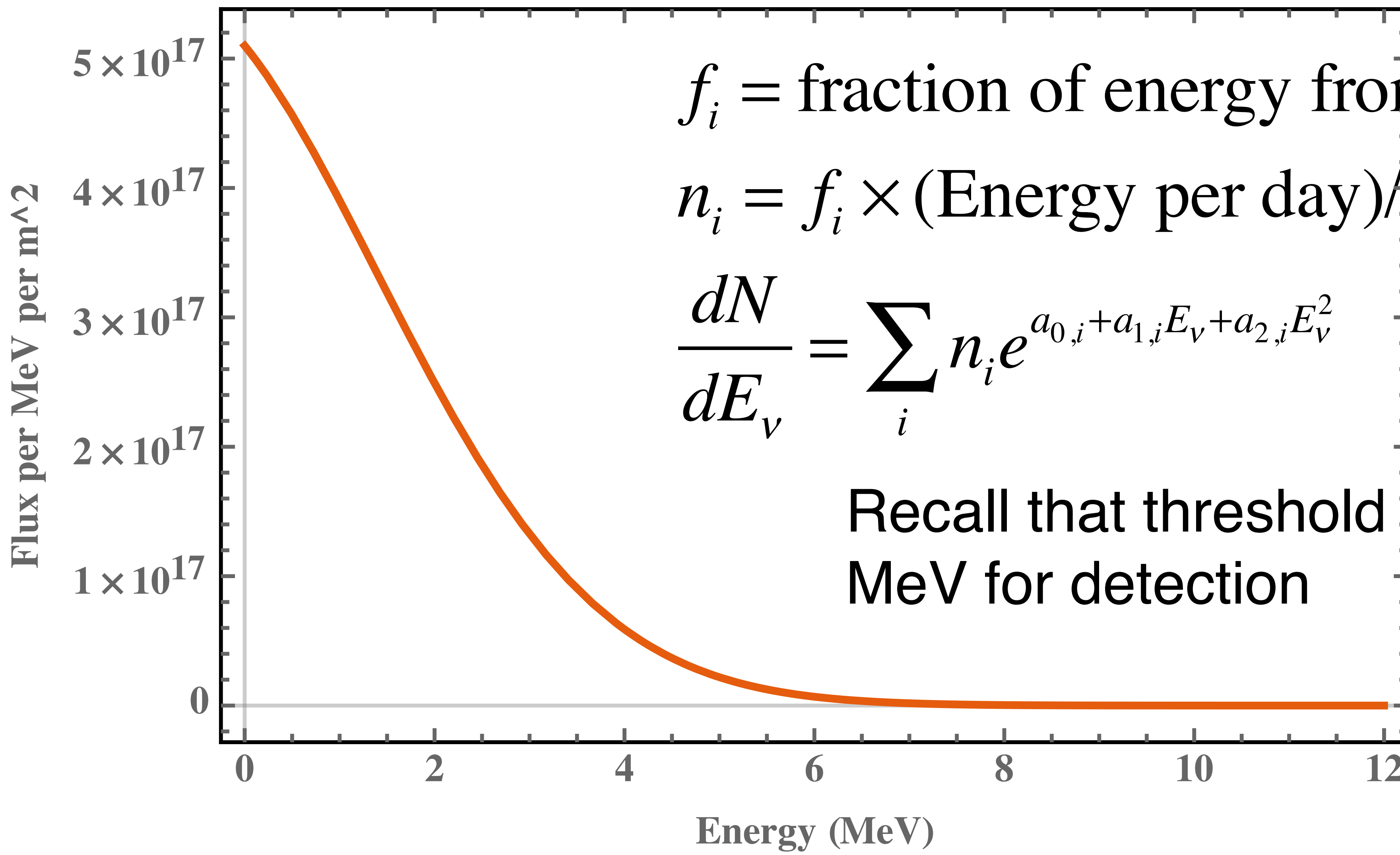
First calculate power produced by each isotope.

In a real experiment the power company will provide this information.

The reactor spectrum parameterization from Vogel and Engel based on data by Schreckenbach.

There are new methods using tabulated beta decay spectra.

Reactor Spectrum



f_i = fraction of energy from isotope i

$n_i = f_i \times$ (Energy per day)/(Energy per fission)

$$\frac{dN}{dE_\nu} = \sum_i n_i e^{a_{0,i}+a_{1,i}E_\nu+a_{2,i}E_\nu^2}$$

Recall that threshold is 1.8 MeV for detection

Isotope	U235	Pu239	U238	Pu241
Energy (MeV)	201.7	205.0	210.0	212.4
a0	0.870	0.896	0.976	0.793
a1	-0.160	-0.239	-0.162	-0.080
a2	-0.0910	-0.0981	-0.0790	-0.1085

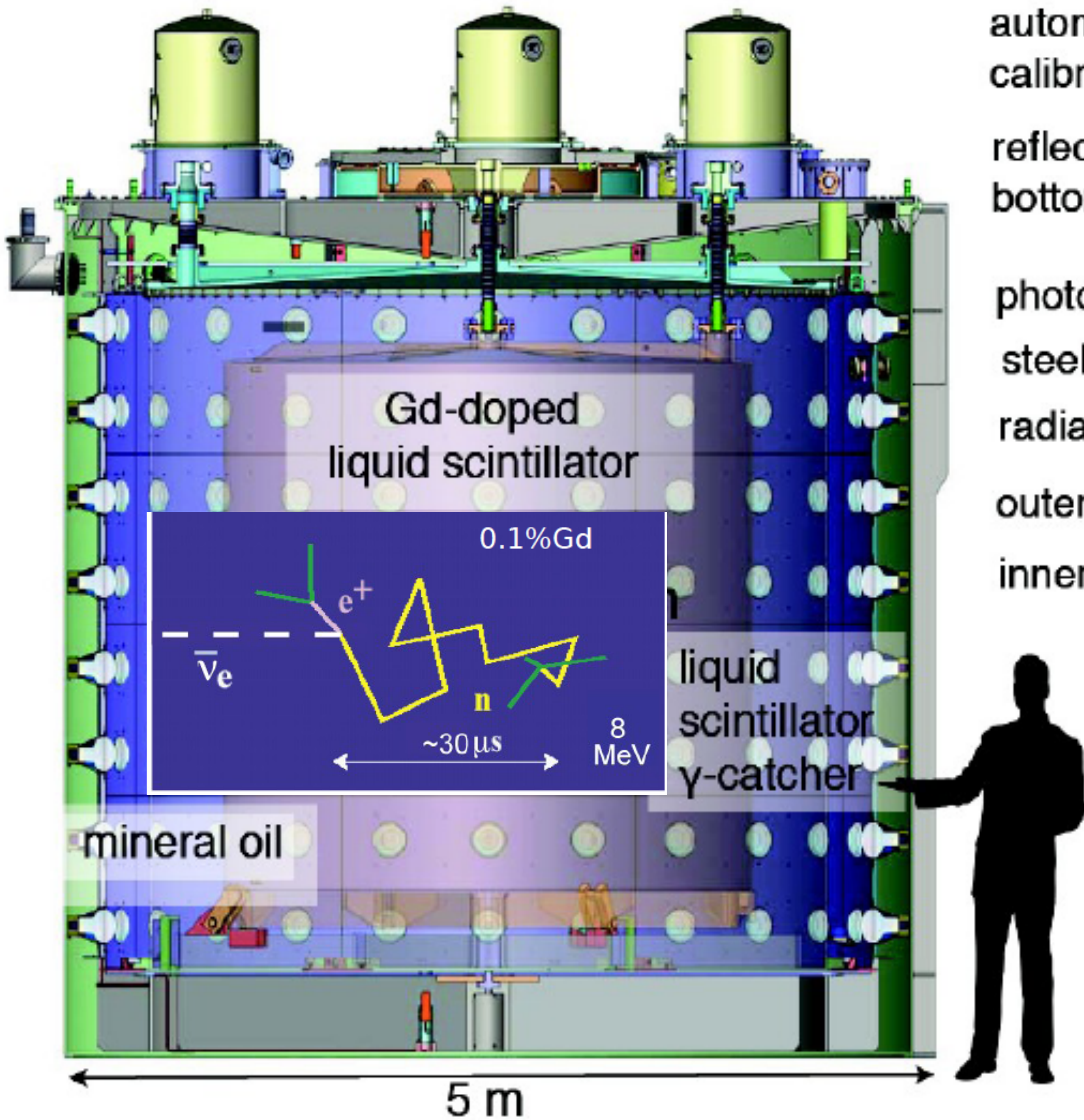
Detector mass needed for 1000 reactor evts/yr ?

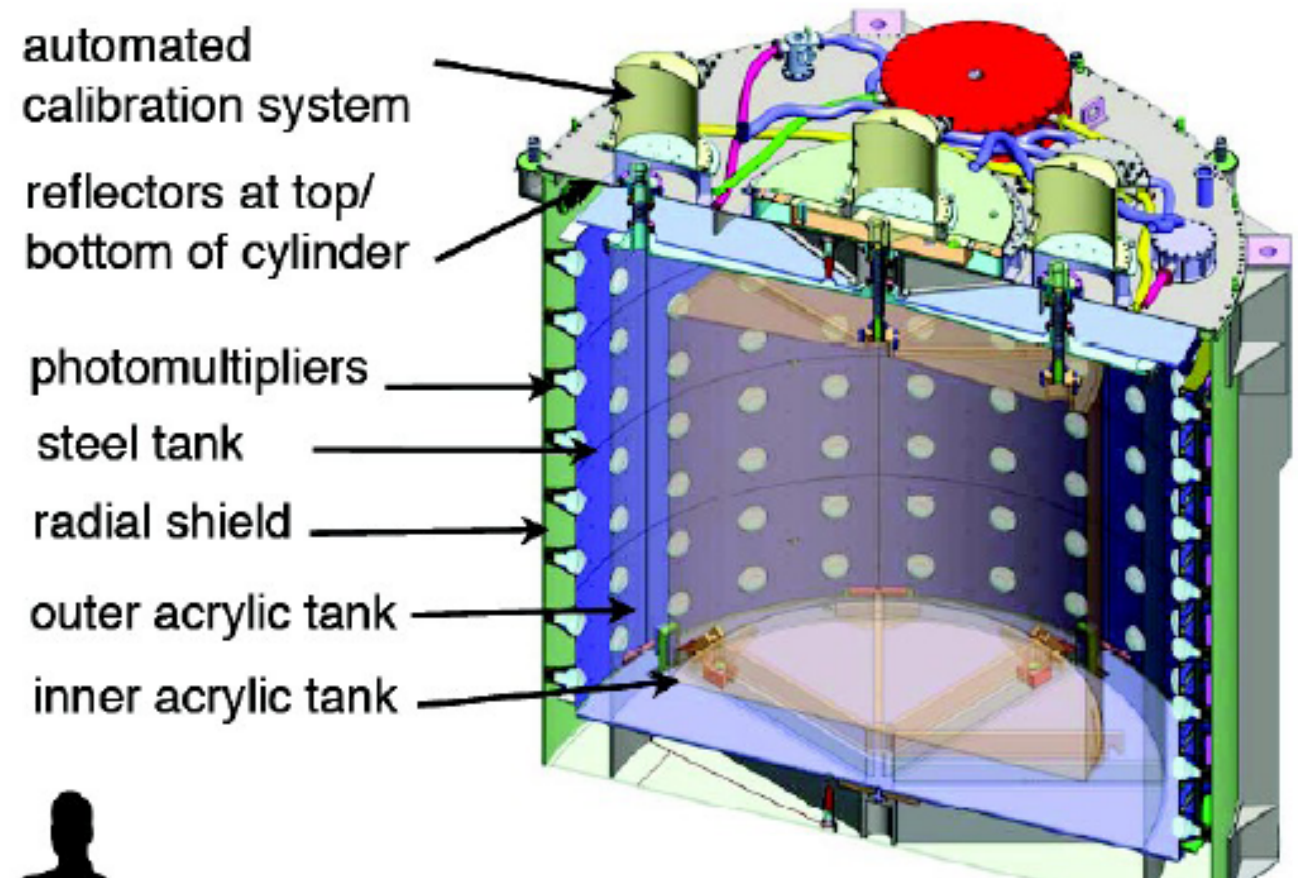
- Detector distance d = 100000 cm. (1 km)
- Yield = 2×10^{20} /sec for GW
- Flux = 1.6×10^{9} /cm^2/sec (assuming 4 pi)
- Protons = (2/3) x 10^{29} /ton
- Fraction above 2 MeV ~ 0.1
- Cross section ~ 0.9×10^{-42} cm^2
- 1 year = 3×10^{7} sec
- N = Flux* Fraction*cross section*Protons/ton*1 year
- N = 290 per ton per year for 1 GW reactor. at 1 km.

Daya Bay Experimental Method

- **Daya Bay has 6 cores each 2.9 GW ➜ 17.4 GW total**
- **The geography is ideal with hills rising away from the bay.**
- **We placed several detectors close to the reactors and several far away to understand neutrino physics called oscillations.**
- **Location is northeast of Hong Kong**

Daya Bay Antineutrino Detectors (AD)





total detector mass: ~ 110t

inner: 20 tons Gd-doped LS (d=3m)

mid: : 22 tons LS (d=4m)

outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8"-PMTs

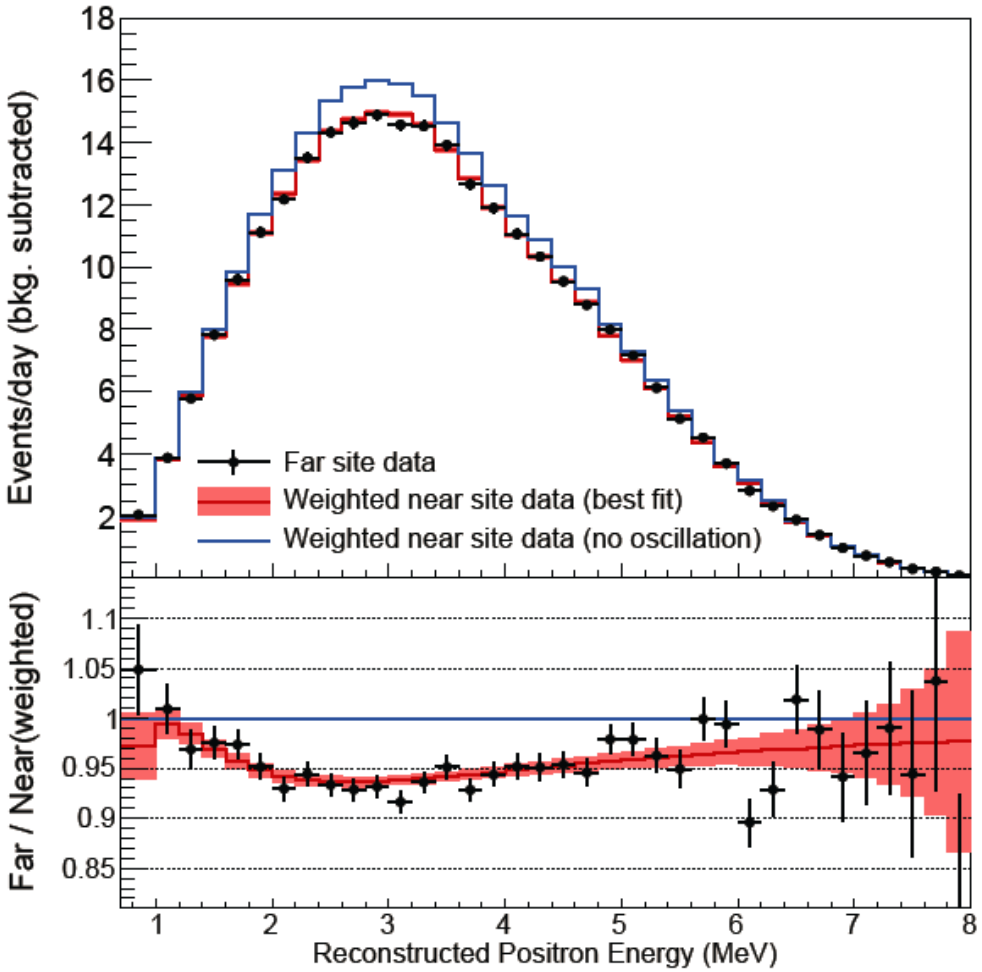
$$Yield = 10^4\, MeV^{-1} \times Coverage \times QE$$

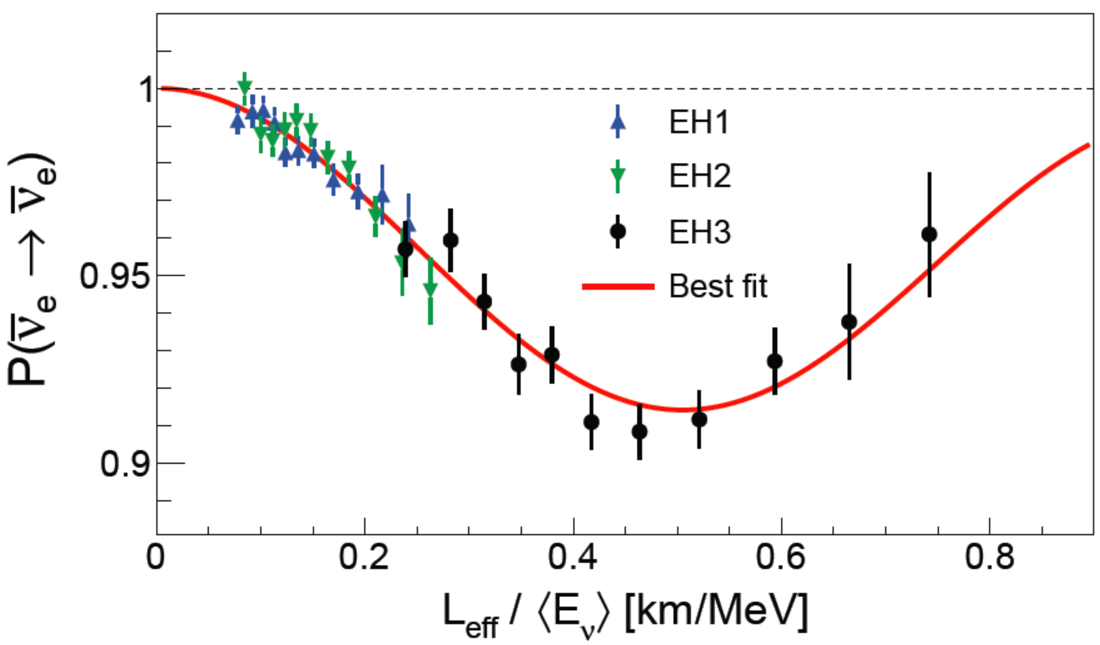
$$= 10^4 \times 0.08 \times 0.2 \sim 160\ pe / MeV$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

Result From Daya Bay with data up to Nov 2013.



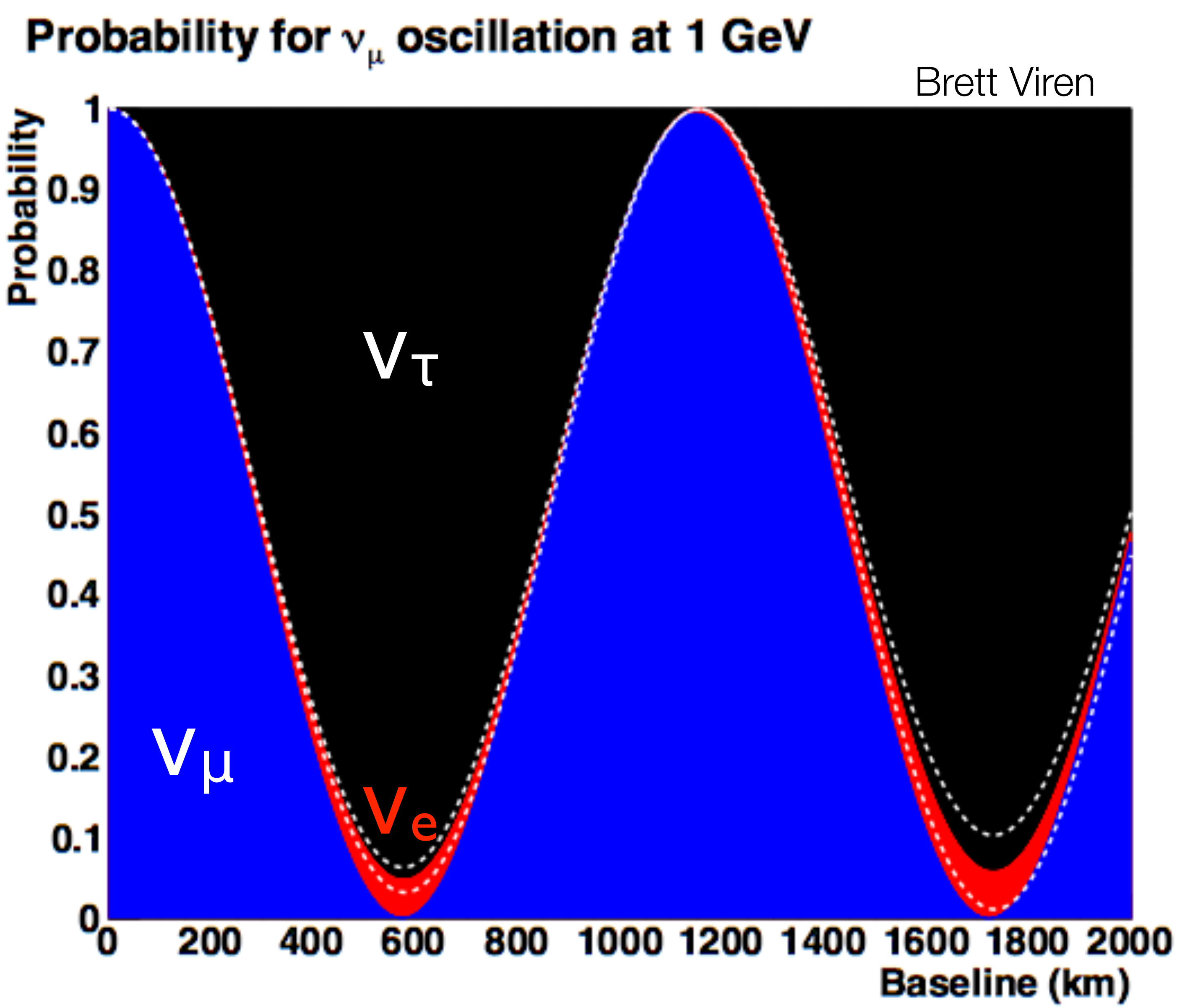


$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$

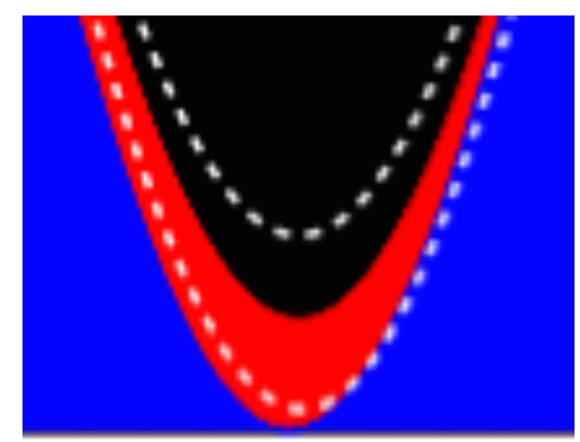
- Using 217 days of 6 AD data and 404 days of 8 AD data.
- Total of 1.2 M events

The full picture of the oscillation effect starting with pure muon type neutrino.



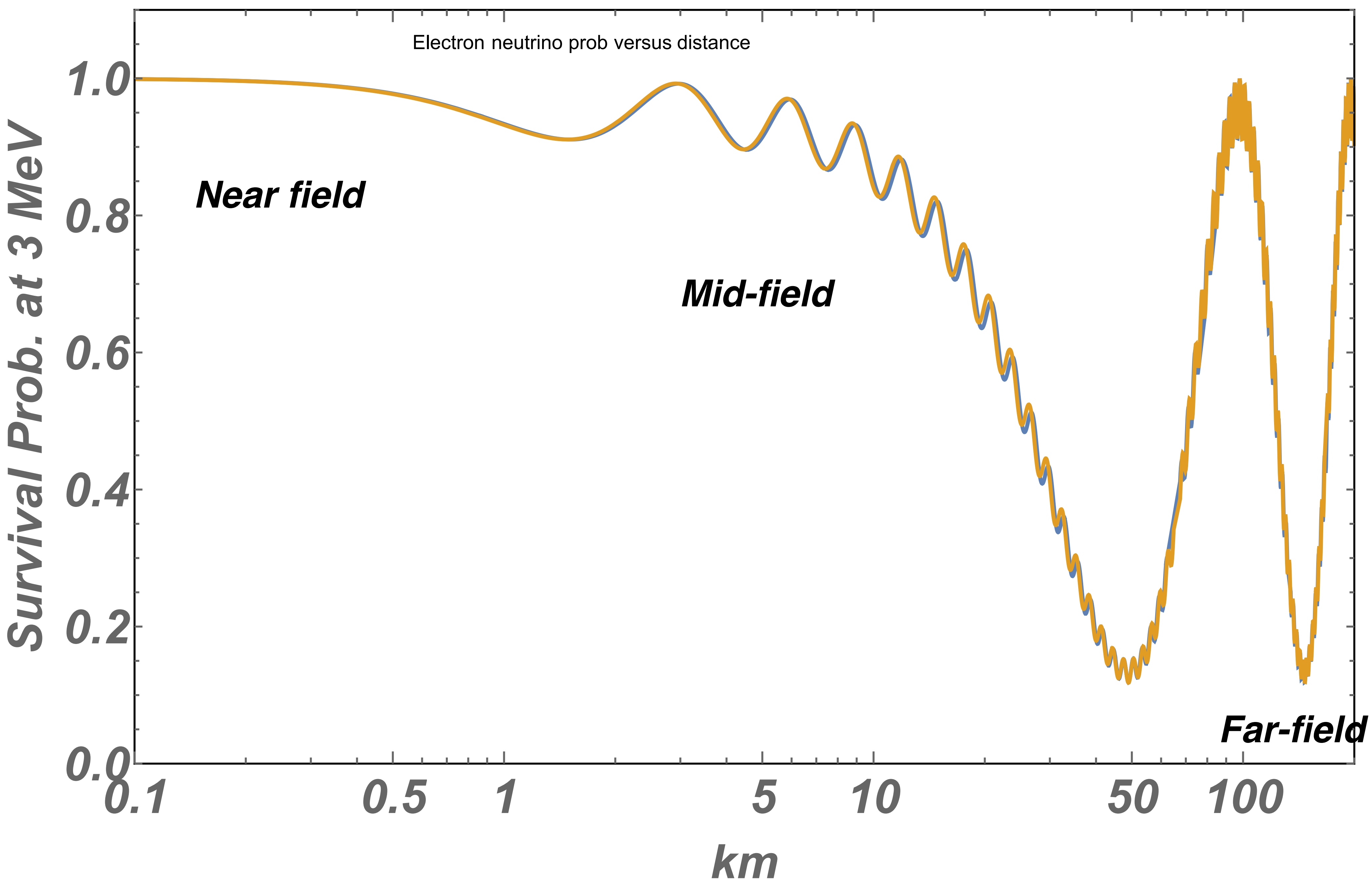
Dashed white lines correspond to CP violation or the unknown phase.

Notice that for sizable effects one needs long distances and large energies.



- There are precise predictions:
  - Large Matter Effects (not yet seen in a laboratory experiment)
  - Potentially large CP violation (not yet seen)

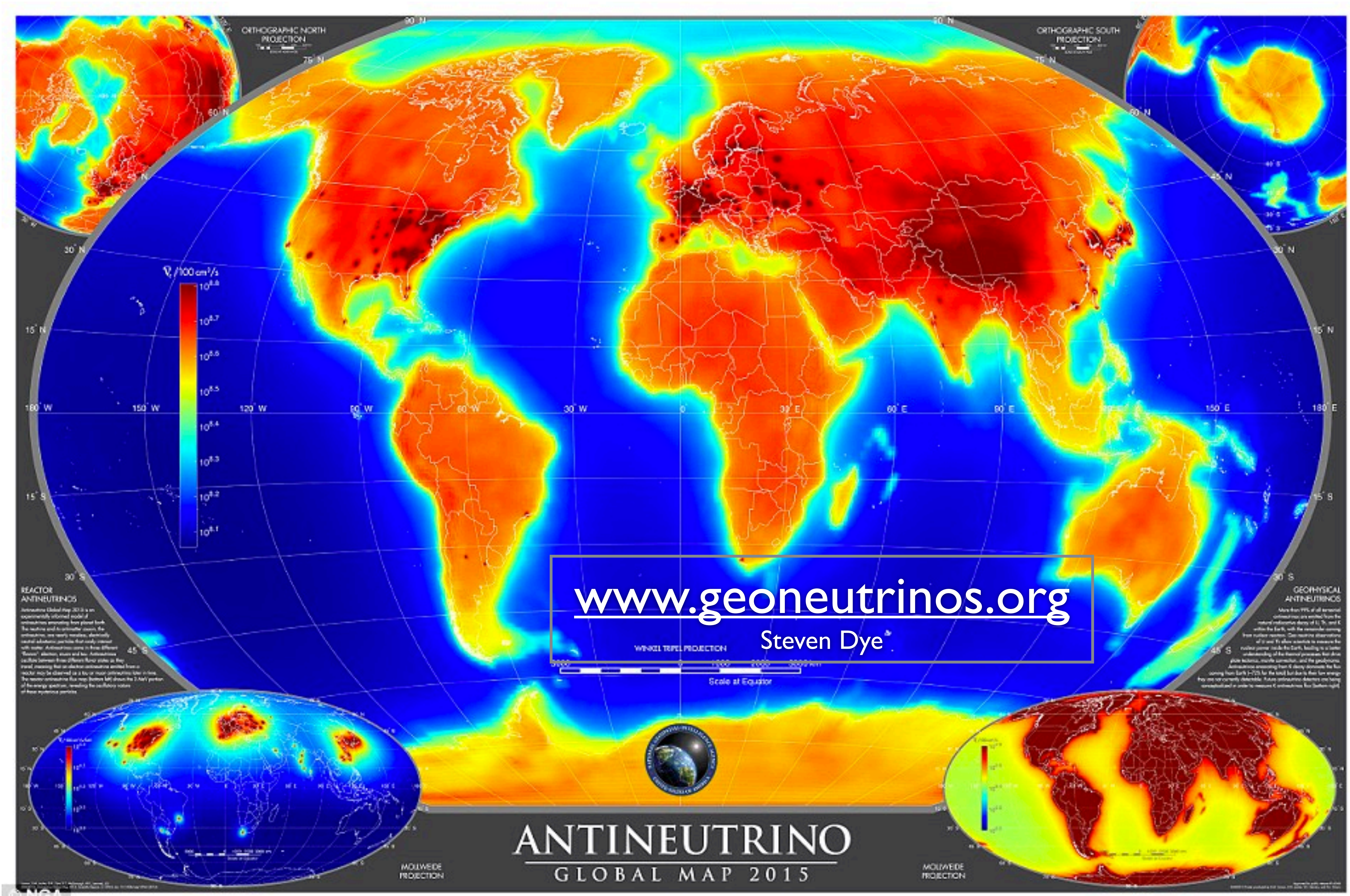
Survival probability for reactor antineutrinos



Application of antineutrino technology ?

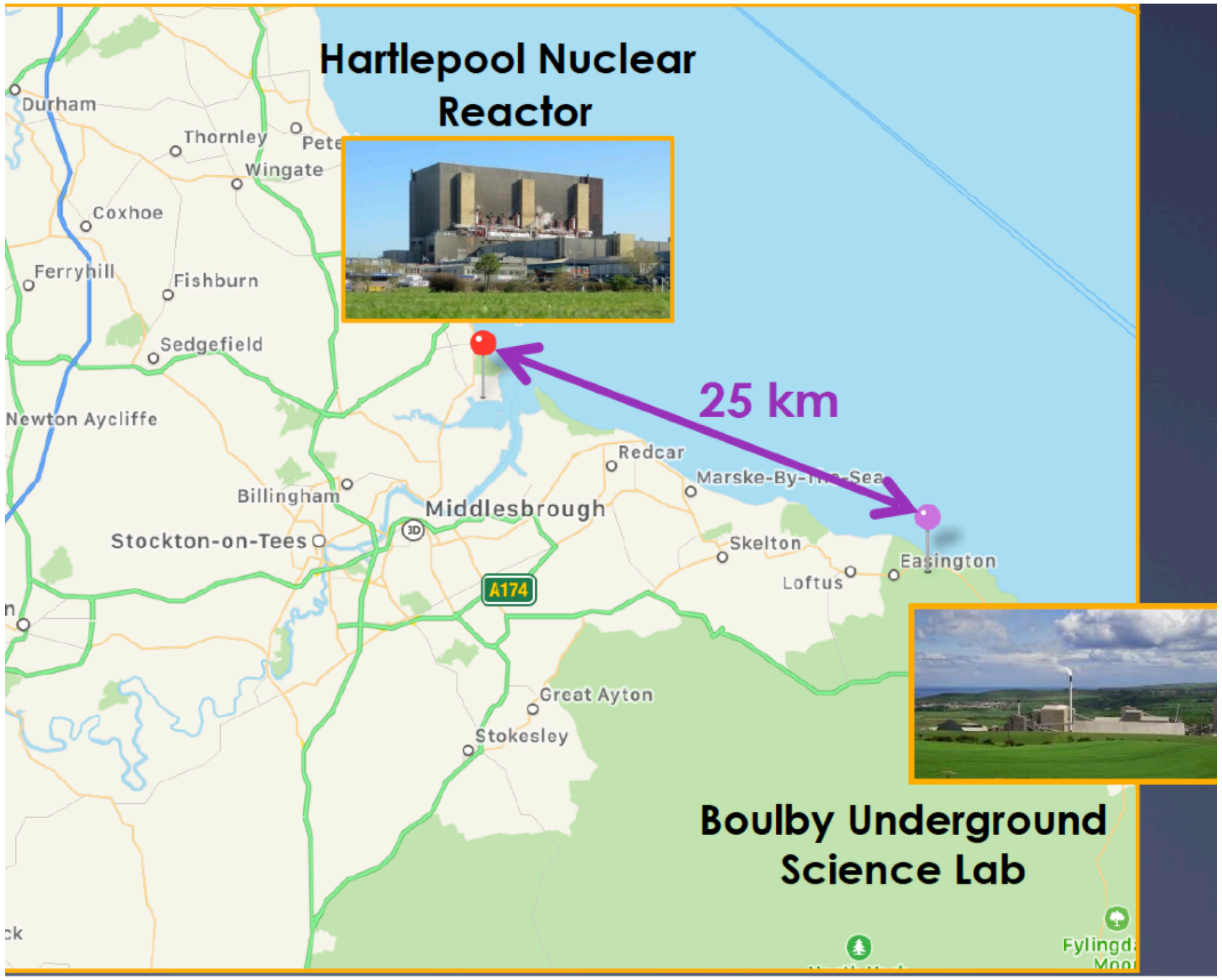
- We now know that each neutrino is a mix of at least 3 mass eigenstates.
- Evolution of a neutrino state is now well know.
- The neutrino state encodes its own range.
- Neutrino detection technology and understanding of backgrounds is now quite advanced.
- Reactor monitoring applications may be possible in certain circumstances.

Can we use neutrinos to see/monitor reactors ? Yes, need to develop inexpensive and effective technologies.



AIT/NEO or Watchman project.

- Remote monitoring demonstration project for a single reactor for non-proliferation.
- Verify, to 3 sigma, the presence of a nuclear reactor within a reasonable period of time.
- Technology: 1 ton scale Gd-loaded water-based anti-neutrino detector located 20-30 km from a fission reactor.
- AIT - Advanced Instrumentation Testbed. NEO- Neutrino Experiment
- Test bench for R&D for detector materials, sensors, electronics, and backgrounds.
- Could include physics topics by additional requirements. Supernova, Solar neutrinos, etc.



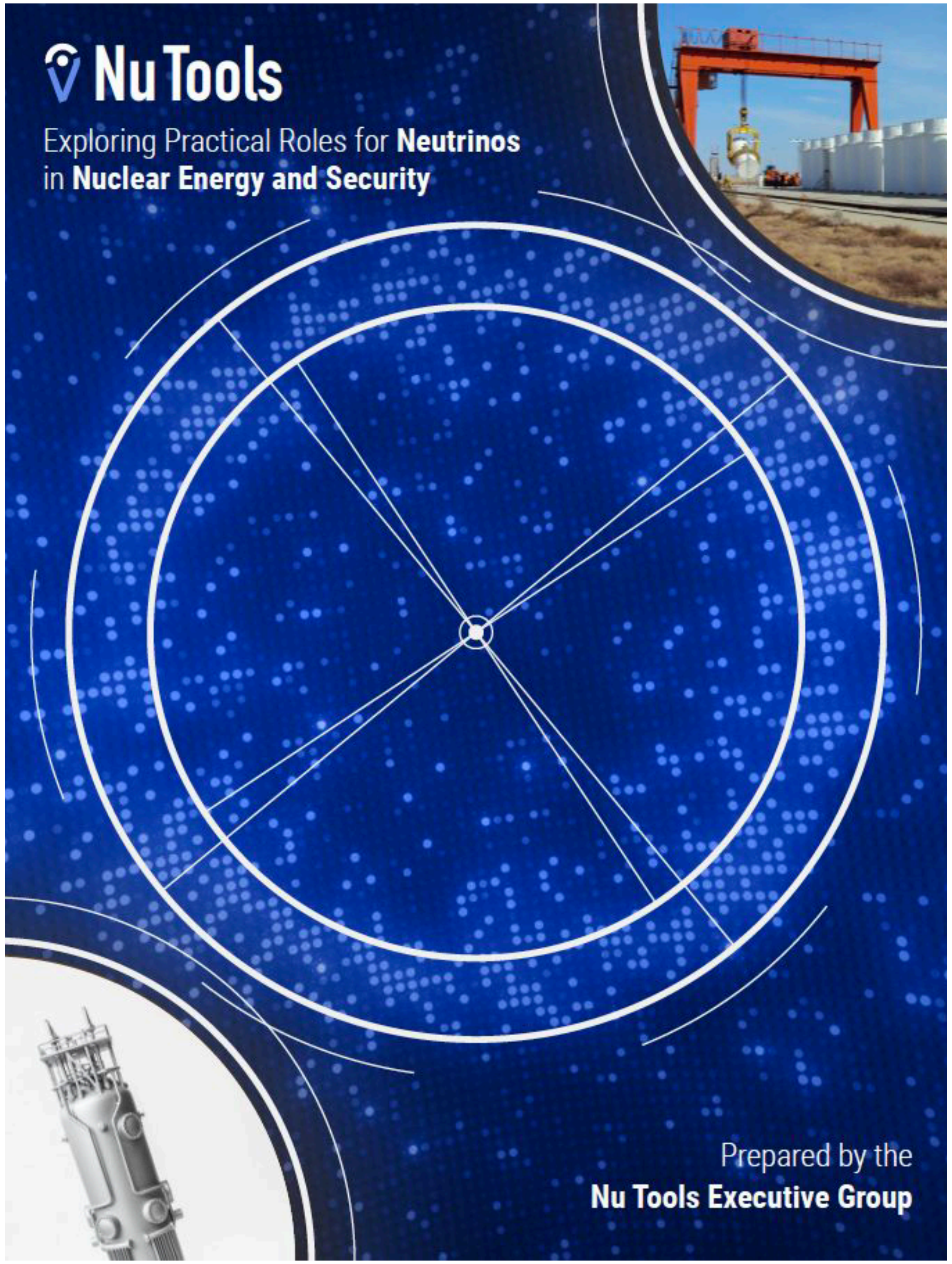
Planned by DOE/DNN and UK/STFC

Location: East Coast of UK.

Due to announced reactor shutdowns this project is no longer going forward. Alternate site in old Morton salt mine near Perry reactor is being examined.

Nu tools report.

- DNNR&D initiated study: "...to facilitate engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities.. .focus… should be on the potential utility of antineutrino detection technologies…in the context of existing or potential policy needs".
- Study took almost 2 years and included extensive interviews with many stakeholders:
    - International safeguards practitioners.
    - Reactor vendors and operators
    - Nuclear policy experts in government agencies and NGOs
- Several mini-workshops were also held.
- Members: T. Akindele, N. Bowden, R. Carr, A. Conant, M. Diwan, A. Erickson, M. Foxe, B. Goldblum, P. Huber, J. Newby, I. Jovanovic, B. Littlejohn, J. Link, P. Mumm



nutools.ornl.gov
https://arxiv.org/abs/2112.12593

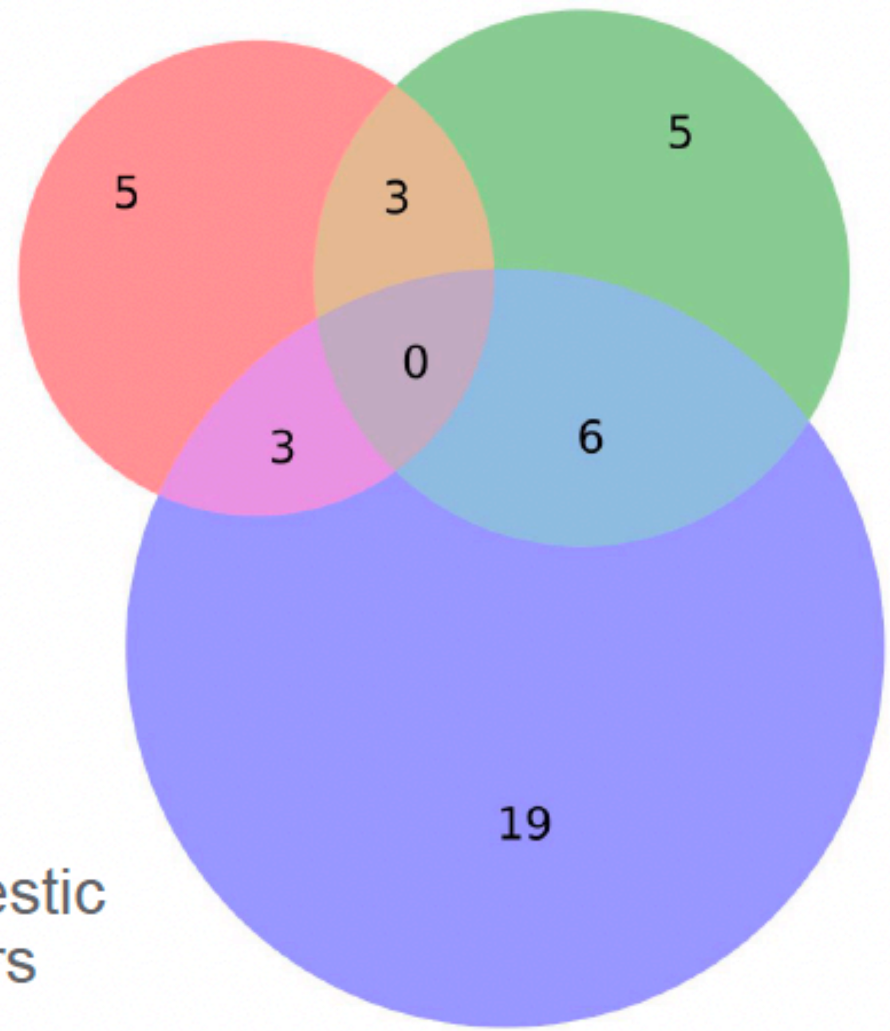
Expert interviews: May 2020-Feb. 2021 (41 individuals)

Neutrino Physics & Technology

Physicists specializing in neutrino application concepts

Reactor Design & Engineering

Nuclear reactor vendors, operators, and researchers



Nuclear Security & Safeguards

- International and domestic safeguards practitioners
- Nuclear policy experts from government agencies and NGOs

Beyond these 41 individuals:

Mini-Workshop with the neutrino community:

- 21 presenters
- >100 more attendees

Nu Tools findings and recommendations

Cross Cutting

End-User Engagement: The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.

Technical Readiness: The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

Neutrino System Siting: Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

We examined following Use Cases in great detail.

ICAEA Safeguards, **Advanced Reactors, Future Nuclear Deals,** Reactor Operations, Non-cooperative nuclear monitoring, **Spent Nuclear Fuel, Post-accident Response.**

More work is needed, but the bold use cases provide very interesting opportunities for R&D

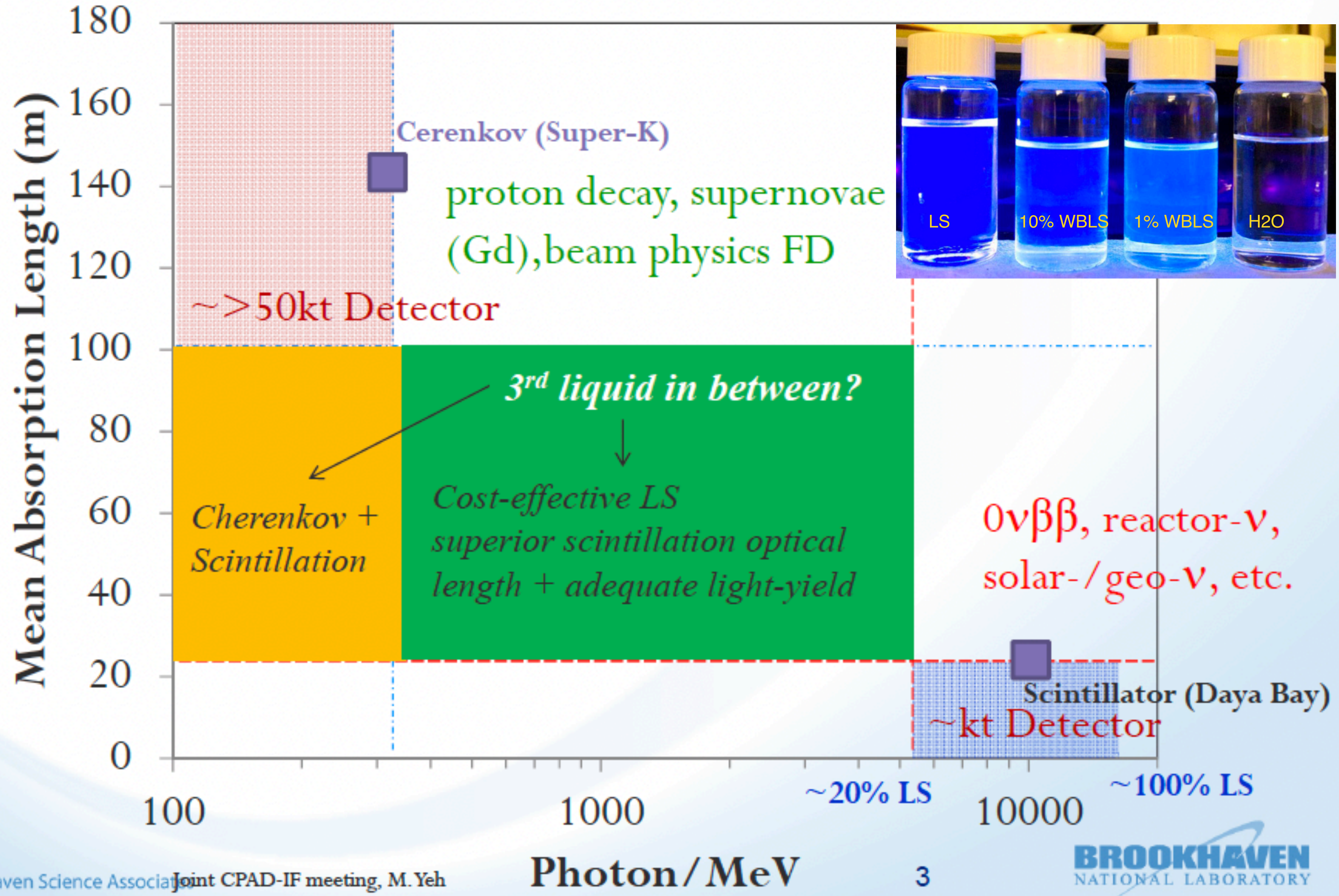
Recommendations

Recommendation for End-User Engagement: DNN should support engagement between neutrino technology developers and end-users in areas where potential utility has been identified.

Recommendation for Technology Development: DNN should lead a coordinated effort among agencies to support a portfolio of neutrino detector system development for areas of potential utility, principally in future nuclear deals and advanced reactors.

BNL Water based liquid scintillator effort is well aligned with the second recommendation.

Cherenkov and Scintillation Detectors



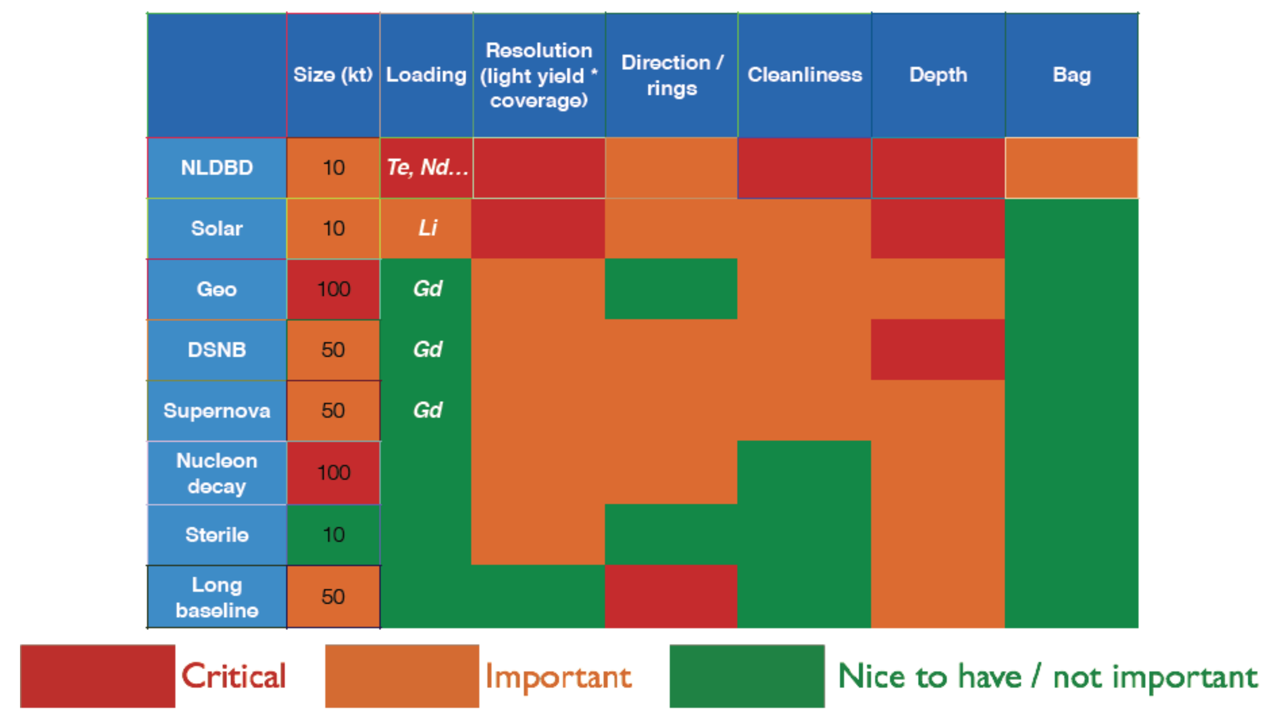
10 years of R&D

- NIM A660 (2011) 51-56, M. Yeh, et al. - A new water-based scintillator.
- JINST 10(2015), 12, P12009, L.J. Bignell, Characterization and modeling .. Also JINST 10 (2015) 10, P10027.
- Report on scientific applications: Alonso et al., 1409.5864 (2014)
- Effort has been supported by DOE-NP, DOE-HEP, and BNL-LDRD.
- Now DNN-R&D has taken particular interest to develop WBLS in collaboration with DOE-HEP as part of the reactor neutrino monitoring program.

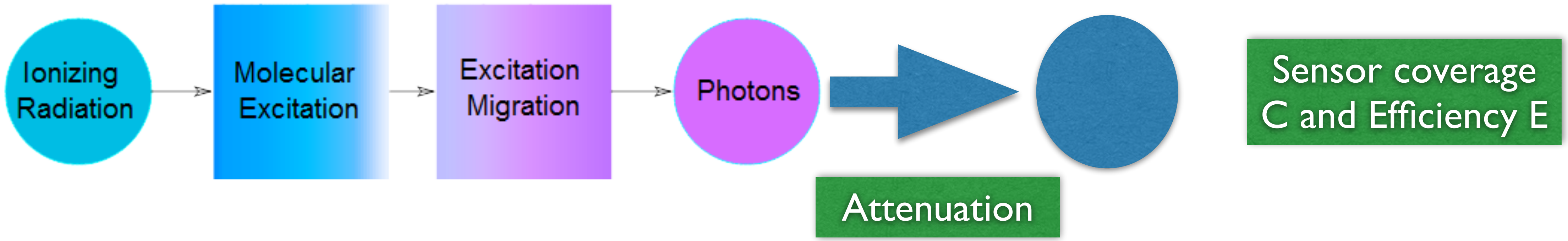
Scientific applications

- Proton Decay. very large mass: 100 kt. Excellent resolution, tracking, timing, and depth.
- Neutrino-less double beta decay: Large mass, excellent low energy resolution, metal loading (130Te).
- Reactor neutrino detection: low energy resolution, Gd loading, detector mass depends on distance from reactor and reactor power.

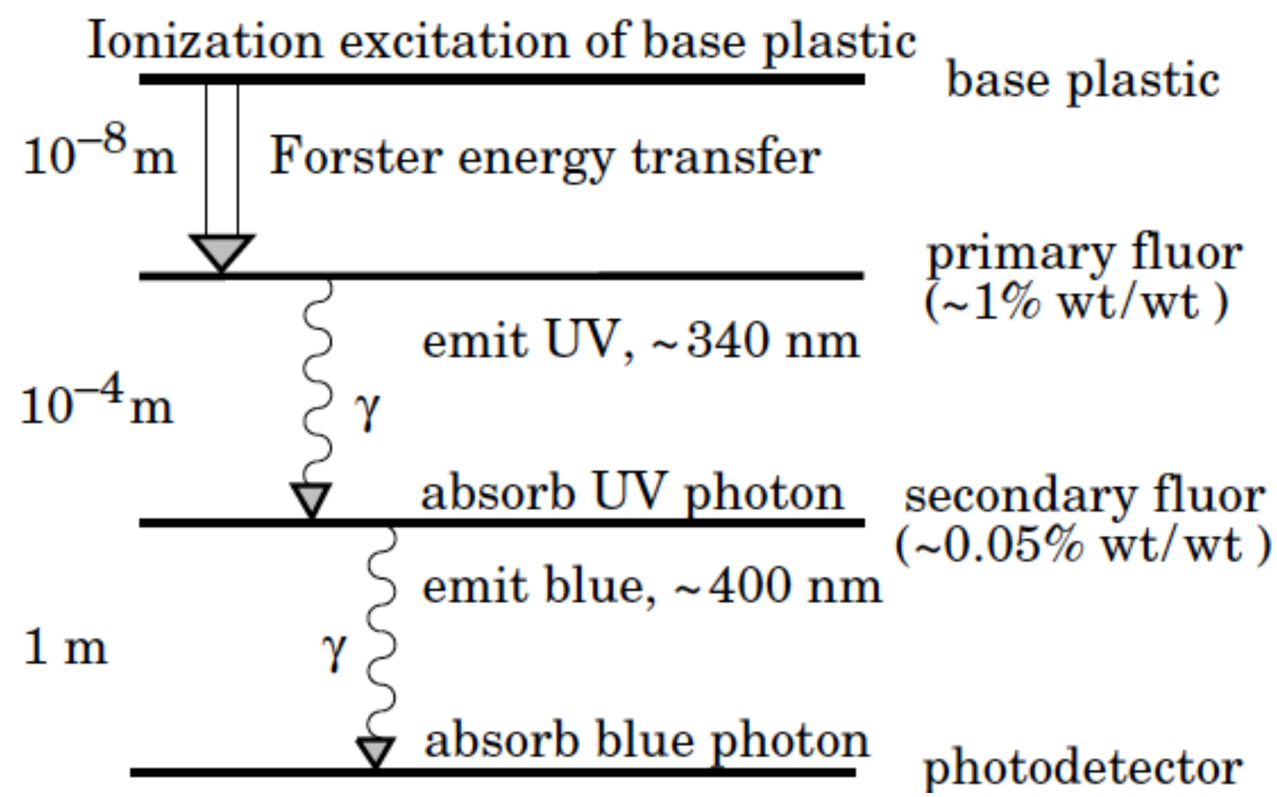
Requirements for different physics topics



Scintillation (organic)



Time scale ~ few ns
due to first fluor



$$\frac{dL}{dx} = L_0 \frac{dE/dx}{1 + k_{Birk} dE/dx}$$

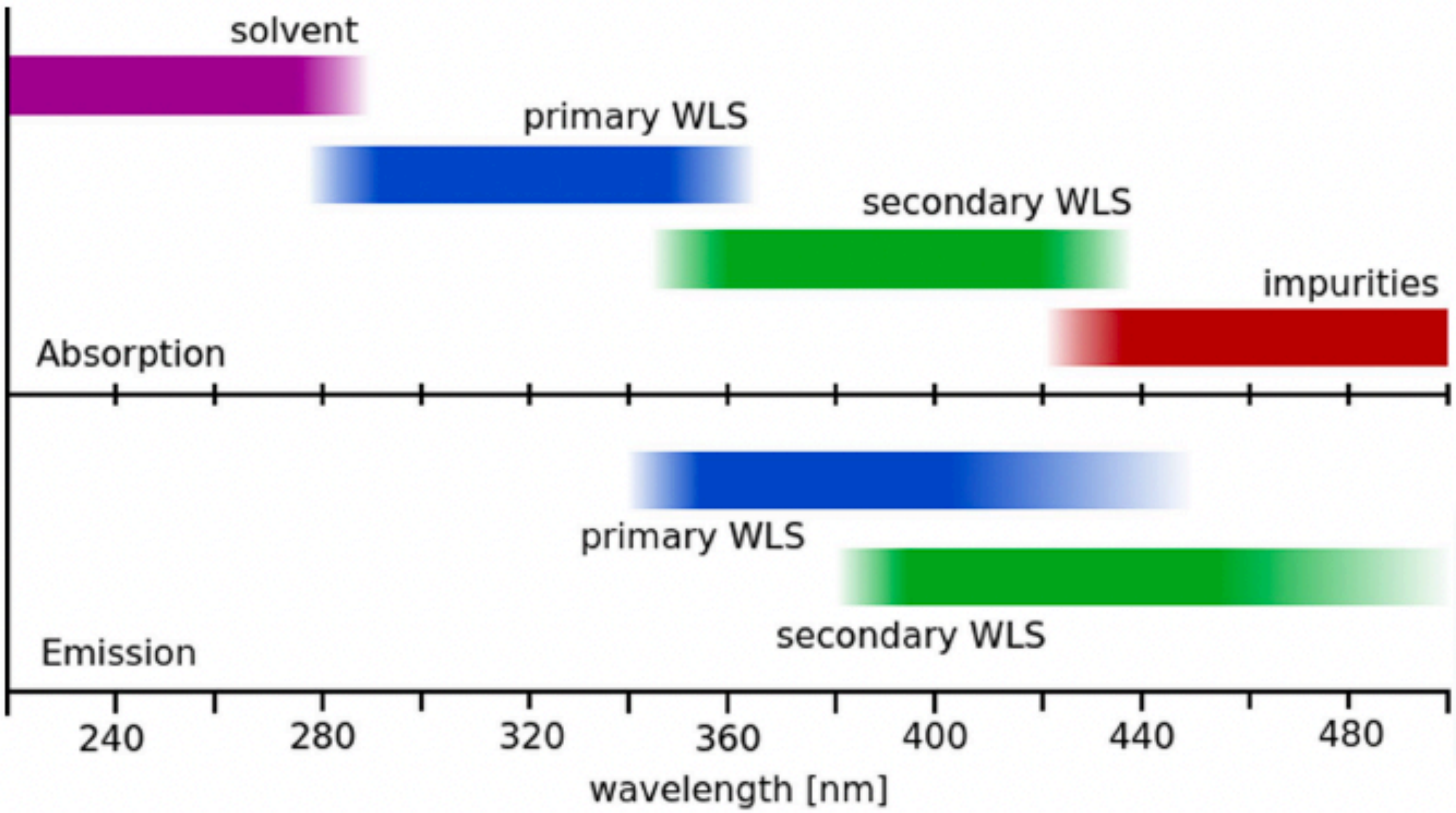
$$Typical \quad L_0 \sim 10^4\, MeV^{-1}$$

$$Yield = L \bullet C \bullet QE \bullet e^{-PathLength/\lambda}$$

- There are many scintillation mechanisms. Organic scintillators and noble liquids are important for neutrino physics.
- S. Hans, J. Cumming, R. Rosero, S. Gokhale, R. Diaz, C. Camilo, M. Yeh, Light-yield quenching and remediation in liquid scintillator detectors, 2020JINST15P12020.
- Inorganic crystal scintillators have not played an important role in neutrino detection.

Scintillator Components

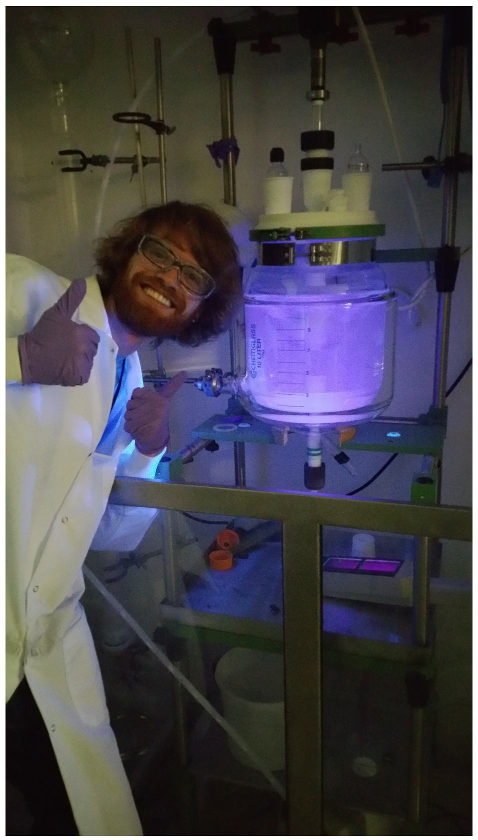
C. Buck and M. Yeh, J. Phys. G: Nucl. Part. Phys. 43 093001 (2016)



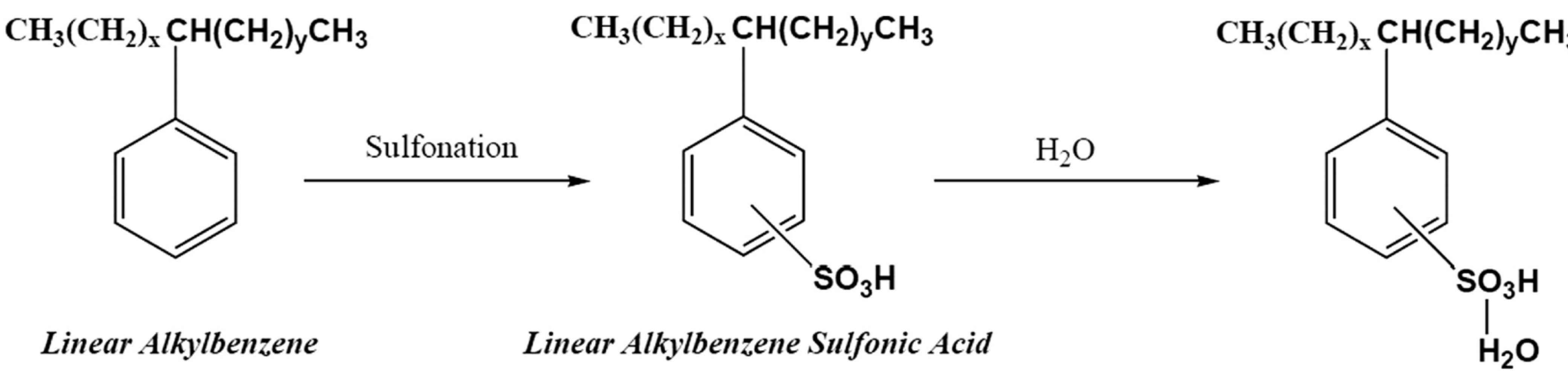
200tons of Daya Bay Gd-LS produced in 2010; stable since production. Transfer ~4 tons to JSNS^2 in 2020/21

- *Key requirements of scintillator detectors for neutrino research: high photon yield, long-term stability, long attenuation length, low toxicity, and high flash point*

Water Based liquid scintillator



- A novel low-energy threshold detection medium bridging scintillator and water.
- Tunable scintillation light from pure water to organic scintillator
- New Hybrid scintillation/Cherenkov particle detector.
- Environmentally friendly with high flash point (for underground installation)
- Cost effective in comparison to LS.
- Various metallic isotopes can be loaded for different physics capability.



Many technical details must be carefully controlled to create a stable material.

Current Program Overview

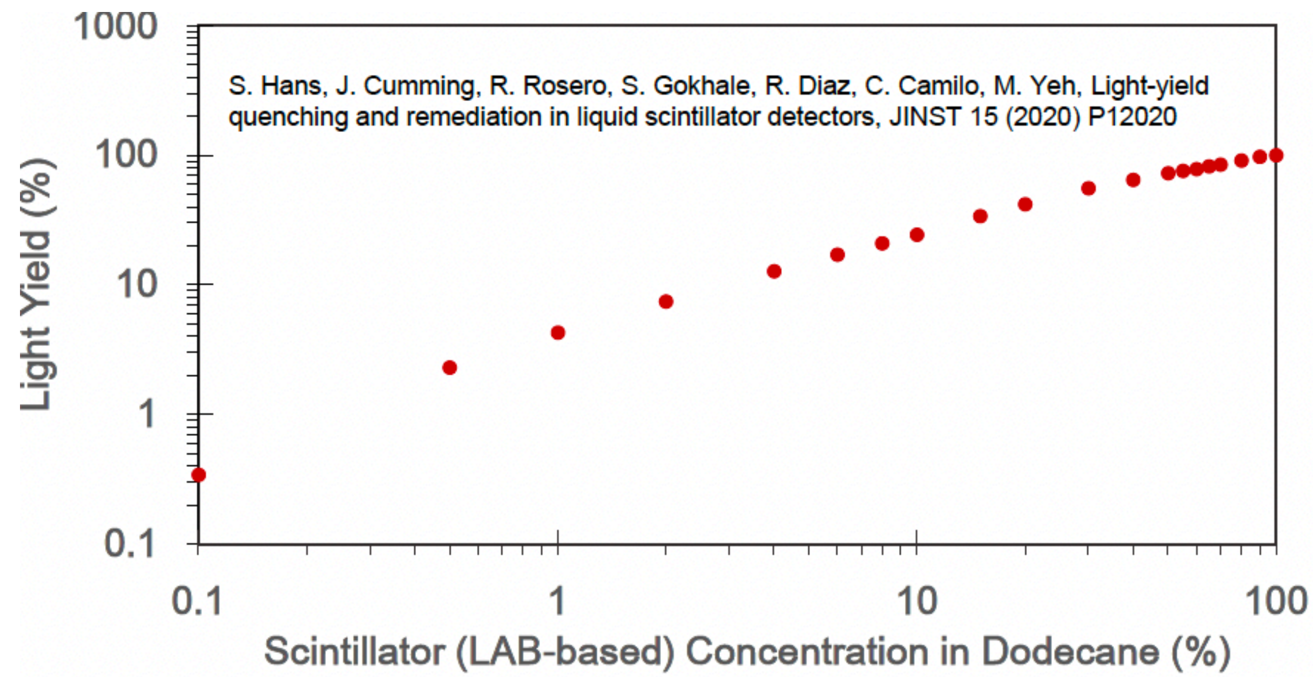
DNN supported LCP (FY22-FY24) aims for readiness of kiloton-scale WbLS deployment:

- 50/50 between Scientific and Prototyping Development
- (A) Scientific Development: Formulation/Characterization development and deployment-scheme development at 1000-liter testbed
  - Status: This is constructed and ready. Going through commissioing phase.
- (B) Prototyping nDevelopment: 30-ton Design Demonstrator; follows BNL SPG (BNL internal directorial review)
  - Status: We are working on design reviews, and procurements.

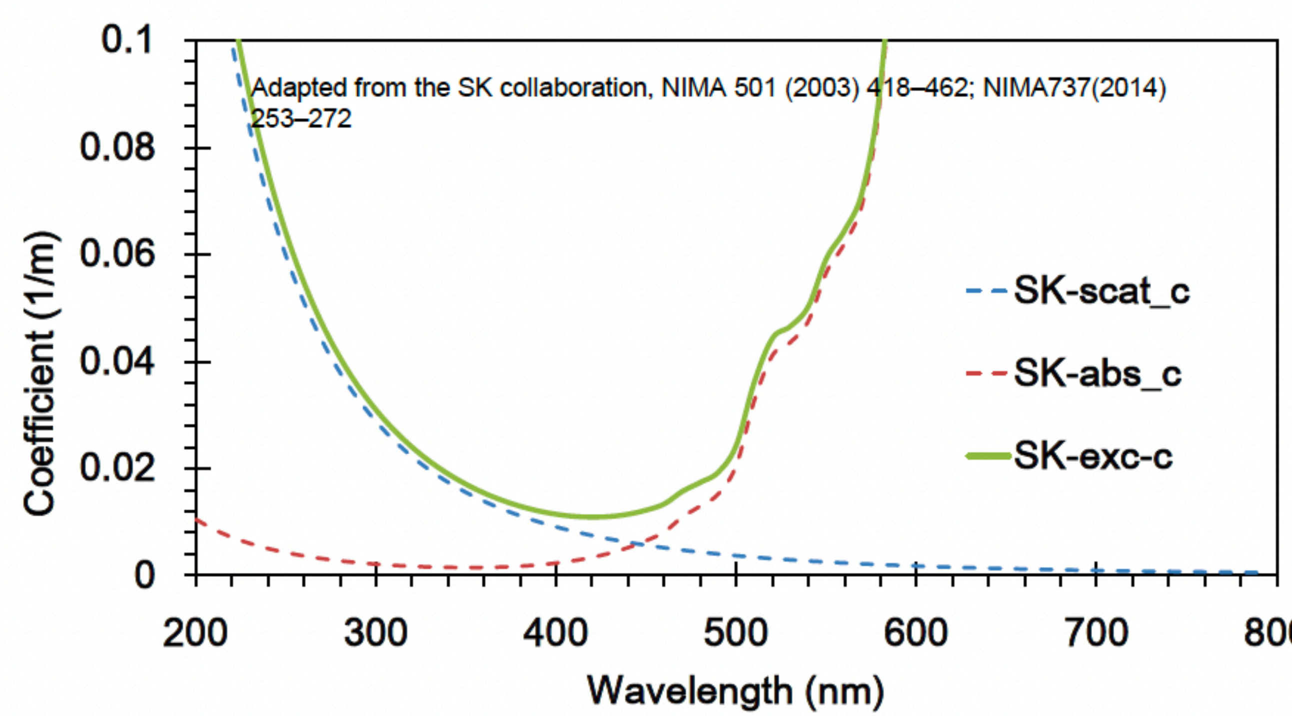
Research Team

- **BNL**
  - M. Yeh, M.V. Diwan, R. Rosero, S. Gokhale, C. Camilo, S. Andrade, N. Seberg, W. Smith, N. Speece-Moyer, B. Walsh, X. Xiang
  - A diverse research team from Chemistry, Physics, and Instrumentation
- **Collaborators**
  - LBNL/UC Berkeley, LLNL, UC Davis, UC Irvine, SBU, UAlabama, CUNY, PSU, BU and UPenn,…,etc.
  - Other US/UK ANNIE/WATCHMAN/THEIA collaborators
- Benchtop development and characterization → Prototyping study → kiloton-scale (engineering) purification, filtration, and production

Basic idea



If scintillation can be added to pure water at some fractional level, then the excellent transparency of water can be used to build much larger scintillation detectors.



Current Status

Scintillator Yield, *Č/S* Separation, Timing Structure, optical (absorption and scattering),…

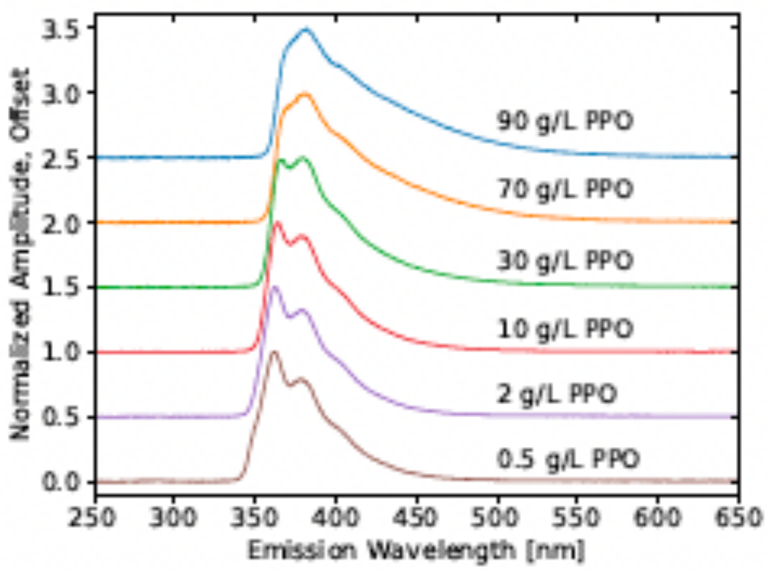


Fig. 1 Emission spectra resulting from X-ray excitation of pure LS with varying concentrations of PPO in LAB. Each curve is displayed normalized at its maximum and offset along the vertical axis.

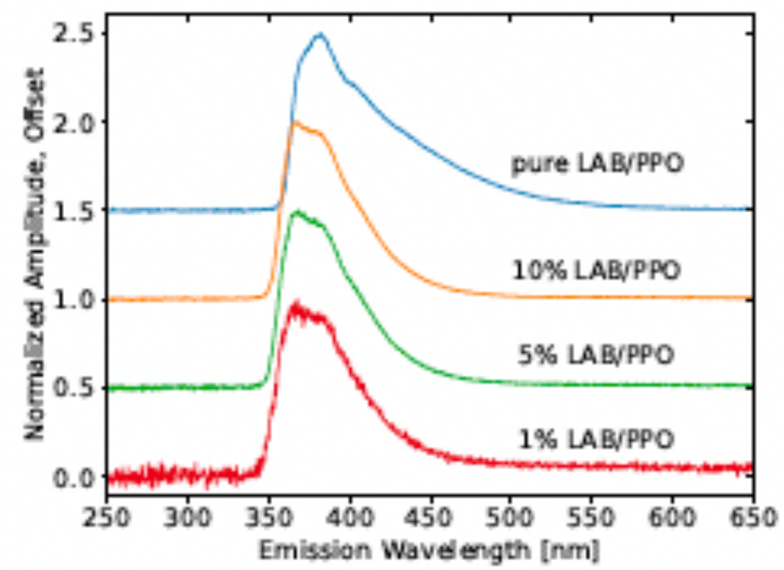


Fig. 2 Emission spectra resulting from X-ray excitation of pure LS (LAB with 90 g/L PPO) and the three WbLS concentrations made from this LS. Each curve is displayed normalized at its maximum and offset along the vertical axis.

Example work.

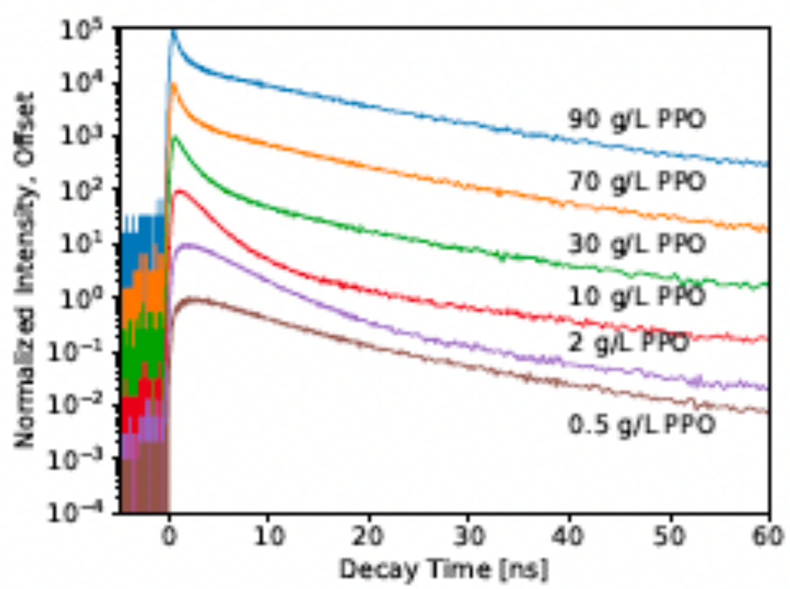


Fig. 3 Time profiles of pure LS for varying concentrations of PPO in LAB from pulsed X-ray excitation. Each curve is normalized by its maximum and then is scaled by a power of 10 to offset along the vertical axis, in order to more clearly show profile shape differences.

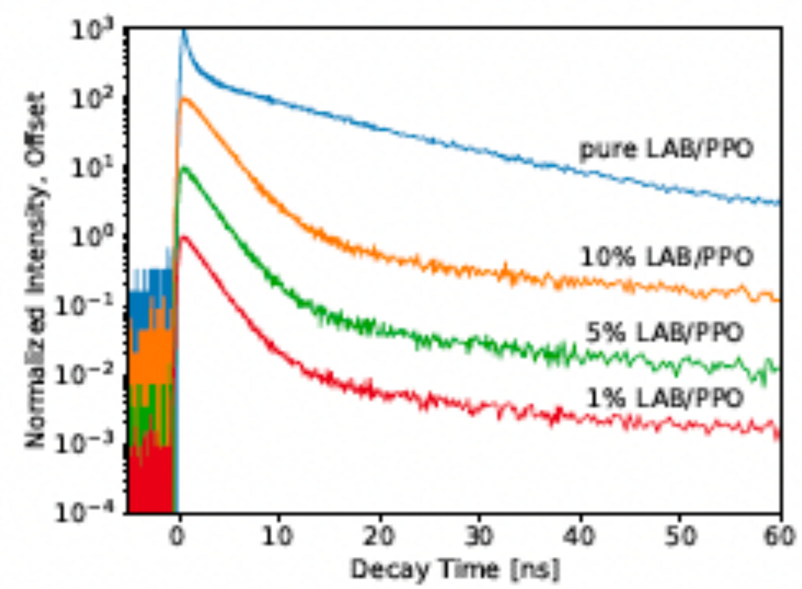


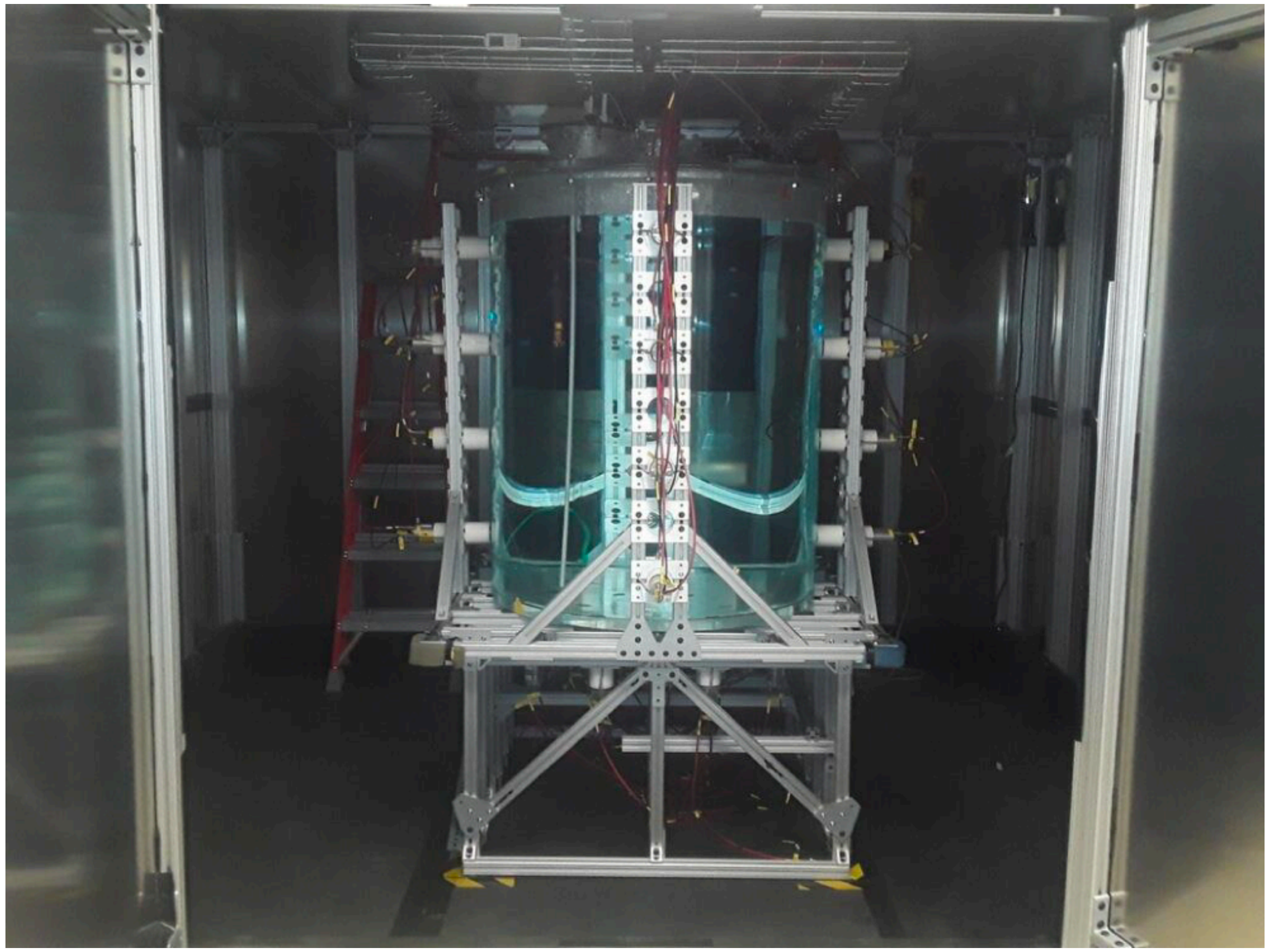
Fig. 4 Time profiles of pure LS (90 g/L PPO in LAB) and the three WbLS concentrations from pulsed X-ray excitation. Each curve is normalized by its maximum and then is scaled by a power of 10 to offset along the vertical axis, in order to more clearly show profile shape differences.

Time Response of Water-based Liquid Scintillator from X-ray Excitation:

Arxiv:2003.10491

Components of 2 ns and ~10 ns are reported for WbLS.

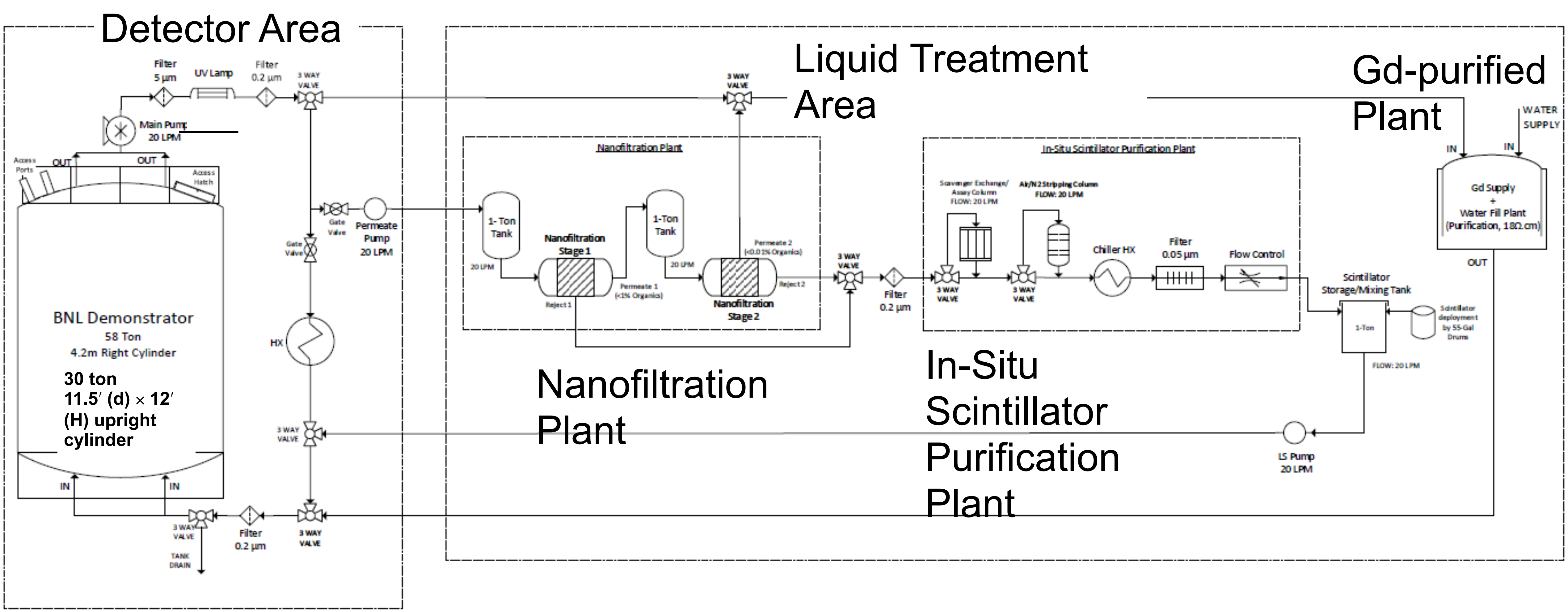
1ton test facility



- Purpose: have a facility to rapidly test WBLS formulations at 1 ton scale.
- Facility must allow high purity for WBLS stability and control.
- Must have enough instrumentation to precisely measure light yield and timing.
- Currently has 32 fast PMTs with 500 MHz readout. And very pure acrylic tank.
- Water system is completely sealed from the environment, with small internal N2 pressure

Purification system achieves 18 MOhm water and then keeps high purity for weeks without needing filtration.

30-T Design Demonstrator CPD

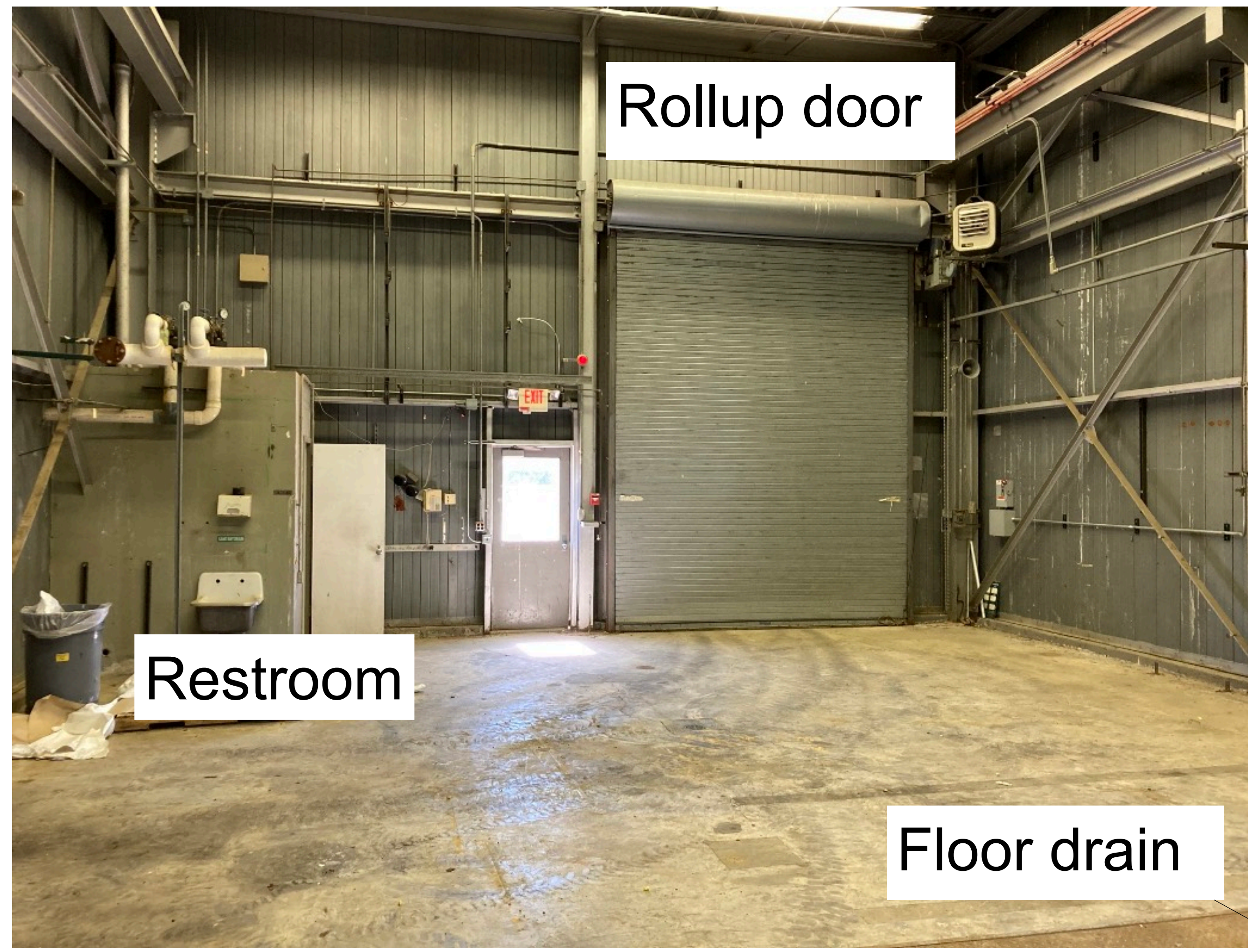


(Main Scope) Derisk GdWbLS (kiloton) deployment and operation:

- *In-situ deployment scheme*
- *Operation parameters (flow rate, turn-over rate, Gd),*
- *Separation and recombination via Nano-filtration system,*
- *Performance stability*
- *Cleanliness, ES&H, and liquid handling training*

National Nuclear Security Administration

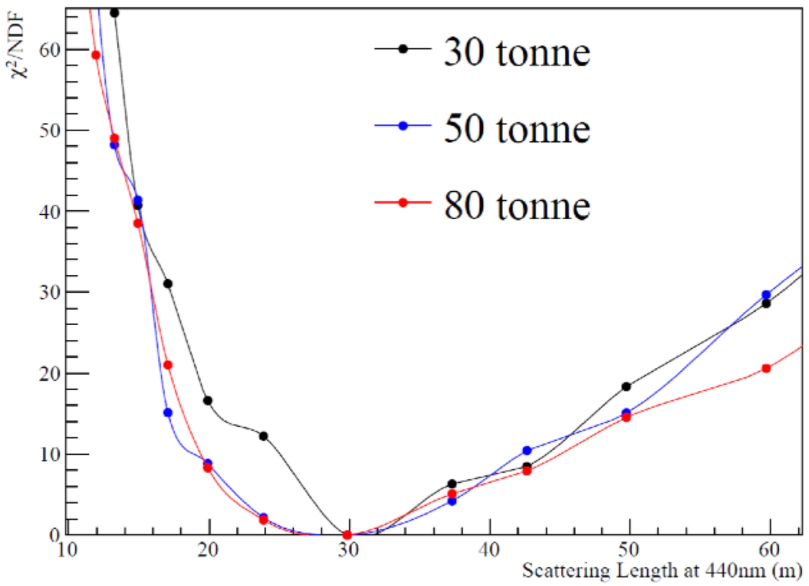
Demonstrator Facility

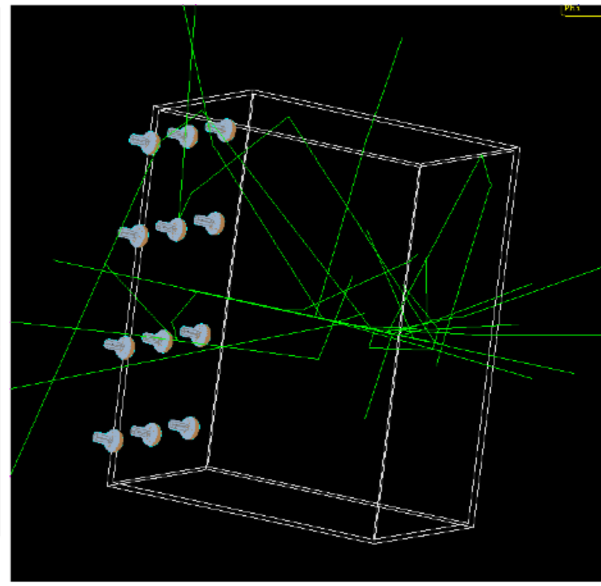


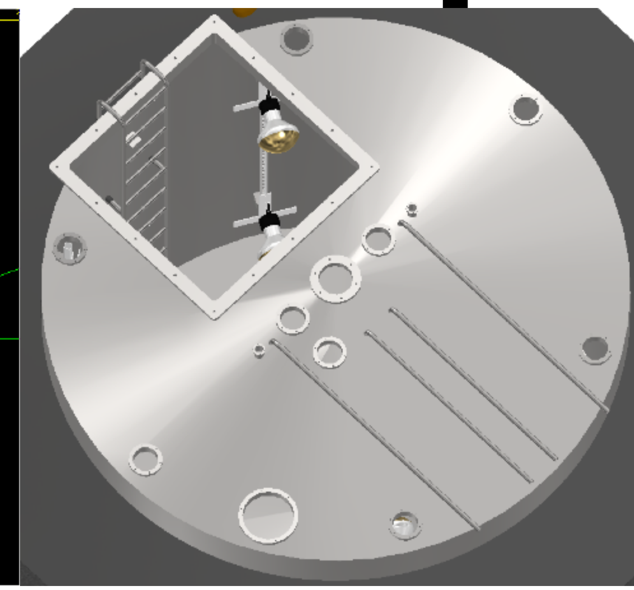
Part of High Flux Beam Reactor Complex; require renovation; Working with BNL MPO to define cost and scopes.

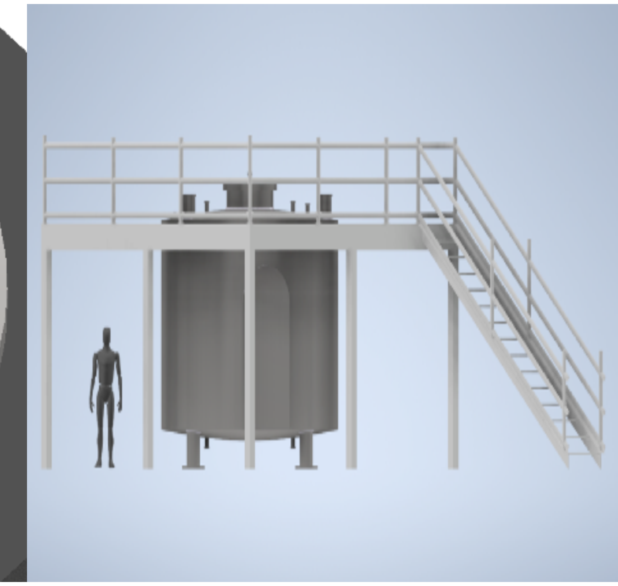
Ceiling height is 23 ft with a non-working crane. Floor, electrical, doors, water supply, network need to be fixed.

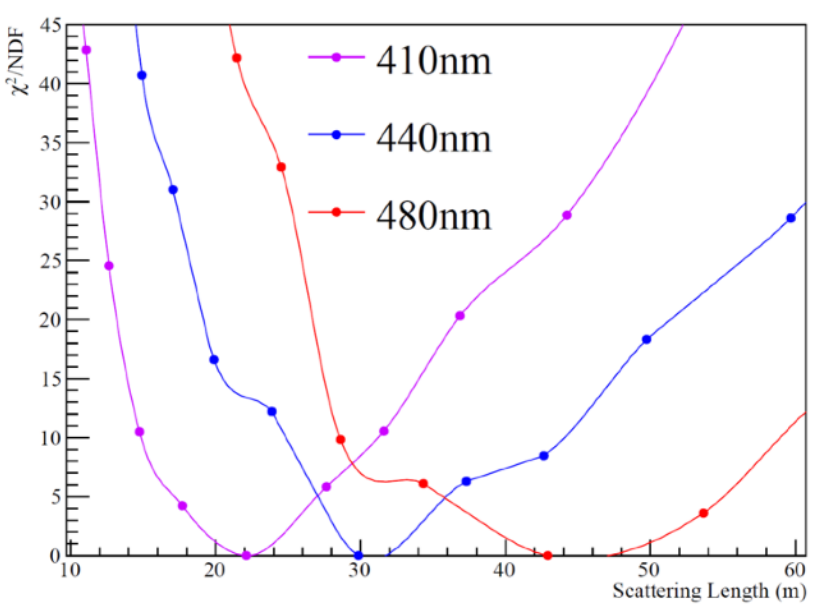
Tank Size & Shape



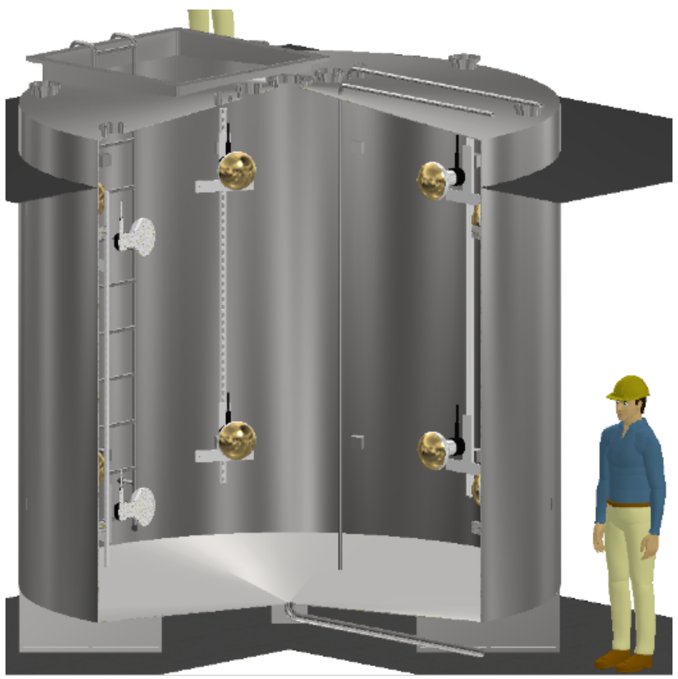








- Simulation to define tank capacity (~30T)
- Engineering design (upright cylinder; SS316 polished); vendor contacts (quotes and feasibility)
- Circulation, Nanofiltration and Gd-water systems are main components attached
- 12-16 10″ PMTs (WbLS-compatible and WM ones)



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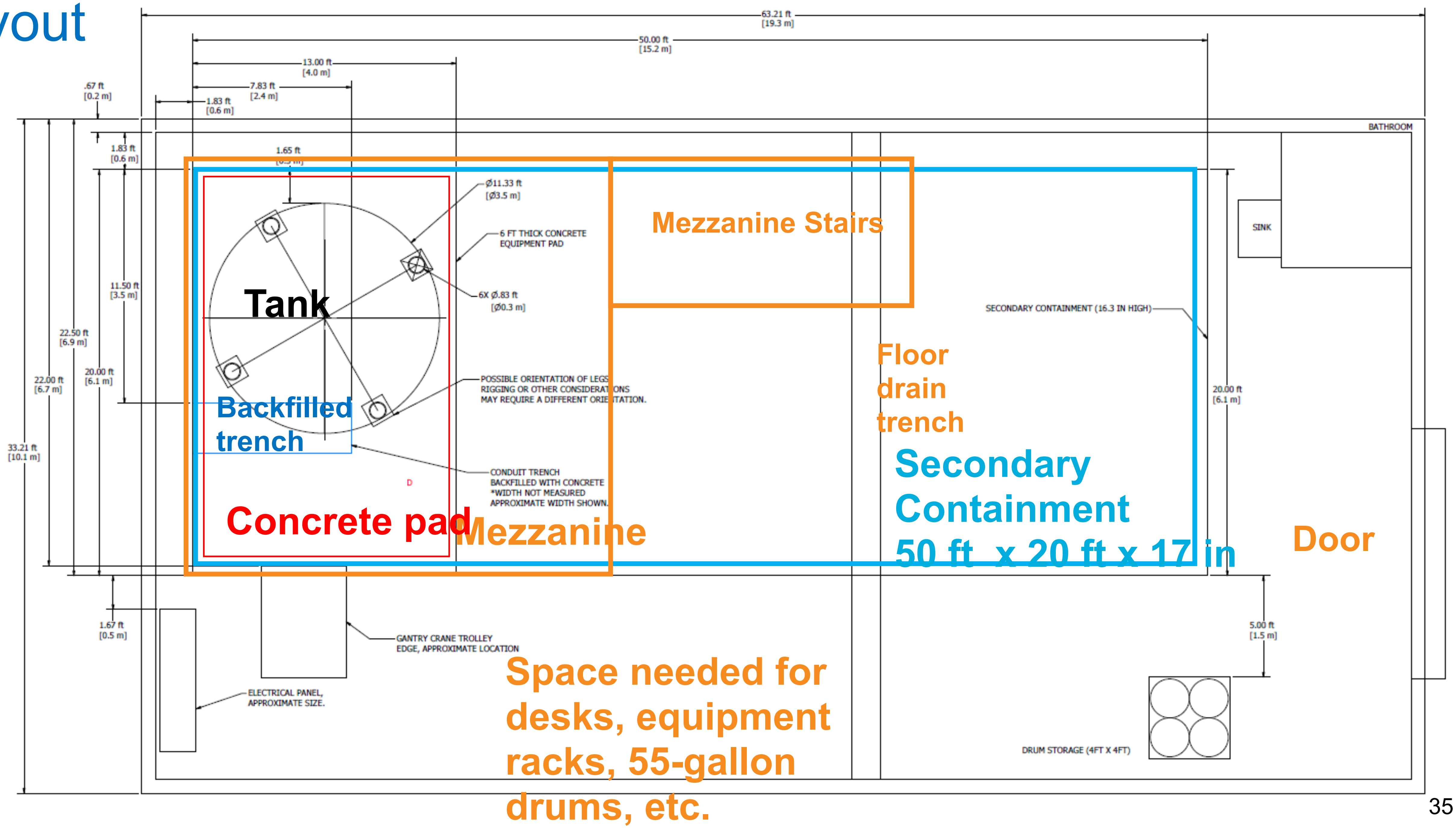
Proposed General Layout



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Conclusion

- **Water base liquid scintillator has several key applications for neutrino physics:**
  - **Cost effective solutions are needed for remote monitoring with neutrinos. WbLS may satisfy this purpose at scales of 10-1000 tons of detector.**
- **BNL chemistry, physics groups have been engaged in R&D on WbLS since 2010.**
- ***Stability and function of the material at small scale has been established.***
- ***Scale-up exercise for fabrication and purification equipment for next steps.***
- ***Commissioning 1-ton testbed (water data-taking)***
  - ***Plan to add nano-filtration (b.top) and increase photo-coverage in FY22***
- ***Design Demonstrator***
  - ***Long-lead items identified***
    - ***Facility renovation (ongoing to maintain scope within budget)***
    - ***Completed Tank FDR (preparation of open-bidding package)***